

Cool Color Roofing Materials

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Cool Color Roofing Materials

A Collaboration of Industry, Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory (ORNL)

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February 24, 2006

Abstract

Raising roof reflectivity from an existing 10-20% to about 60% can reduce cooling-energy use in buildings in excess of 20%. Cool roofs also result in a lower ambient temperature that further decreases the need for air conditioning and retards smog formation. In 2002, suitable cool *white* materials were available for most roof products, with the notable exception of asphalt shingles; cooler *colored* materials are needed for all types of roofing. To help to fill this gap, the California Energy Commission (Energy Commission) engaged Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL) to work on a three-year project with the roofing industry to develop and produce reflective, colored roofing products. The intended outcome of this project was to make cool-colored roofing materials a market reality within three to five years. For residential shingles, we have developed prototype light-colored shingles with solar reflectances of up to 35%. One manufacturer currently markets colored shingles with the ENERGY STAR qualifying solar reflectance of 0.25. Colored metal and clay tile roofing materials with solar reflectances of 0.30 to 0.60 are currently available in the California market.

LBNL and ORNL performed research & development in conjunction with pigment manufacturers, and worked with roofing materials manufacturers to reduce the sunlit temperatures of nonwhite asphalt shingles, clay tiles, concrete tiles, metal products, and wood shakes. A significant portion of the effort was devoted to identification and characterization of pigments to include and exclude in cool coating systems, and to the development of engineering methods for effective and economic incorporation of cool pigments in roofing materials. The project also measured and documented the laboratory and in-situ performances of roofing products. We also established and monitored three pairs of demonstration homes to measure and showcase the energy-saving benefits of cool roofs. The following activities were carried out.

In collaboration with the Energy Commission, we convened a Project Advisory Committee (PAC), composed of 15 to 20 diverse professionals, to provide strategic guidance to the project.

In order to determine how to optimize the solar reflectance of a pigmented coating matching a particular color, and how the performance of cool-colored roofing products compares to that of a standard material, we (1) measured and characterized the optical properties of many standard and innovative pigmentation materials; (2) developed a computer model to maximize the solar reflectance of roofing materials for a choice of visible colors; and (3) created a database of characteristics of cool pigments.

In order to help manufacturers design innovative methods to produce cool-colored roofing materials, we (1) compiled information on roofing materials manufacturing methods; (2) worked with roofing manufacturers to design innovative production methods for cool-colored materials; and (3) tested the performance of materials in weather-testing facilities.

One of the project objectives was to demonstrate, measure and document the building energy savings, improved durability and sustainability attained by use of cool-colored roof materials to key stakeholders (consumers, roofing manufacturers, roofing contractors, and retail home improvement centers). In order to do this, we (1) monitored buildings at California demonstration sites to measure and document the energy savings of cool-colored roof materials; (2) conducted materials testing at weathering farms in California; (3) conducted thermal testing at the ORNL Steep-slope Assembly Testing Facility; and (4) performed a detailed study to investigate the effect of solar reflectance on product useful life.

We developed partnerships with various members of the roofing industry. We worked through the trade associations to communicate and advertise to their membership new cool color roof technology and products. This collaboration induced the manufacturers to develop a market plan for California and to provide technical input and support for this activity. Through the industry partners, many California housing developers and contractors have been convinced to install the new cool-colored roofing products.

Acknowledgement

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This work has been a collaborative research between ORNL, LBNL, and the industry. We acknowledge the contribution of Tony Chiovare (Custom-Bilt Metals), Lou Hahn (Elk Corporation), Ingo Joedicke (ISP Minerals), Frank Klink (3M Industrial Minerals), Scott Kriner (Akzo Nobel Coatings), Kenneth Loye (Ferro), David Mirth (Owens Corning), Jeffrey Nixon (Shepherd Color Company), Joe Reilly (American Rooftile Coating), Robert Scichili (then BASF Industrial Coatings, currently a consultant to coated metal industry), Ming L. Shiao (CertainTeed), Krishna Srinivas (GAF), Yoshihiro Suzuki (MCA Clay Tile), Jerry Vandewater (Monier Lifetile), Michelle Vondran (Steelscape), Lou R. Zumpano (Hanson Roof Tile).

We also acknowledge the guidance, support, and the directives of the Project Advisory Committee (PAC) members: Gregg Ander (Southern California Edison Company), Aaron J. Becker (Dupont Titanium Technologies), Carl Blumstein (California Institute for Energy and Environment), Tom Bollnow (National Roofing Contractors Association), Jack Colbourn (US EPA SF Office), Kathy Diehl (US EPA SF Office), Steven Harris (Quality Auditing Institute), Noah Horowitz (Cool Roof Rating Council and National Resource Defense Council), Scott Kriner (Cool Metal Roofing Coalition), Scott Kriner (Cool Metal Roofing Coalition), Shari Litow (DuPont Titanium Technologies), Archie Mulligan (Habitat for Humanity), Mike Evans (Evans Construction), Jerry Wager (Ochoa & Shehan), Rick Olson (Roof Tile Institute), Mike Rothenberg (Bay Area Air Quality Management District), Steven Ryan (US EPA), Thomas A. Shallow (Asphalt Roofing Manufacturers Association), Peter Turnbull (Pacific Gas and Electric Company), Jessica C Yen (DuPont Titanium Technologies).

Executive Summary

The world is facing disruptive global climate change from greenhouse gas emissions and increasingly expensive and scarce energy supplies. Energy efficiency reduces those emissions and mitigates the rising cost of energy. Energy-Efficient Cool Color Roofing is a new technology for the roofs of homes that provides a significant leap in energy efficiency. The application of this technology for developing cool-colored roofing materials has been the focus of this collaborative study between the scientists at the Lawrence Berkeley National Laboratory (LBNL), scientists at Oak Ridge National Laboratory (ORNL), and industry.

Cool Color Roofing uses solar-reflective pigments to reduce a home's solar heat gain and air-conditioning energy consumption in a warm climate by about 10 to 20%. These roofs also lower a home's peak-hour cooling power demand by about 10 to 20%, helping prevent blackouts and brownouts on hot summer afternoons. We used pigment spectroscopy to identify solar-reflective pigments of different colors and developed software for the design of cool color coatings. We collaborated with a consortium of U.S. pigment, coating and roofing manufacturers to develop novel methods to manufacture asphalt shingle, clay tile, concrete tile, and metal roofing products in a wide palette of cool colors. We estimate that applying cool-colored roofs to houses could achieve a net energy savings in the U.S. worth over \$400 million per year (Konopacki et al. 1997). The estimated savings in California (in 2005 \$) is about \$100 million per year (see Figure EX-1).

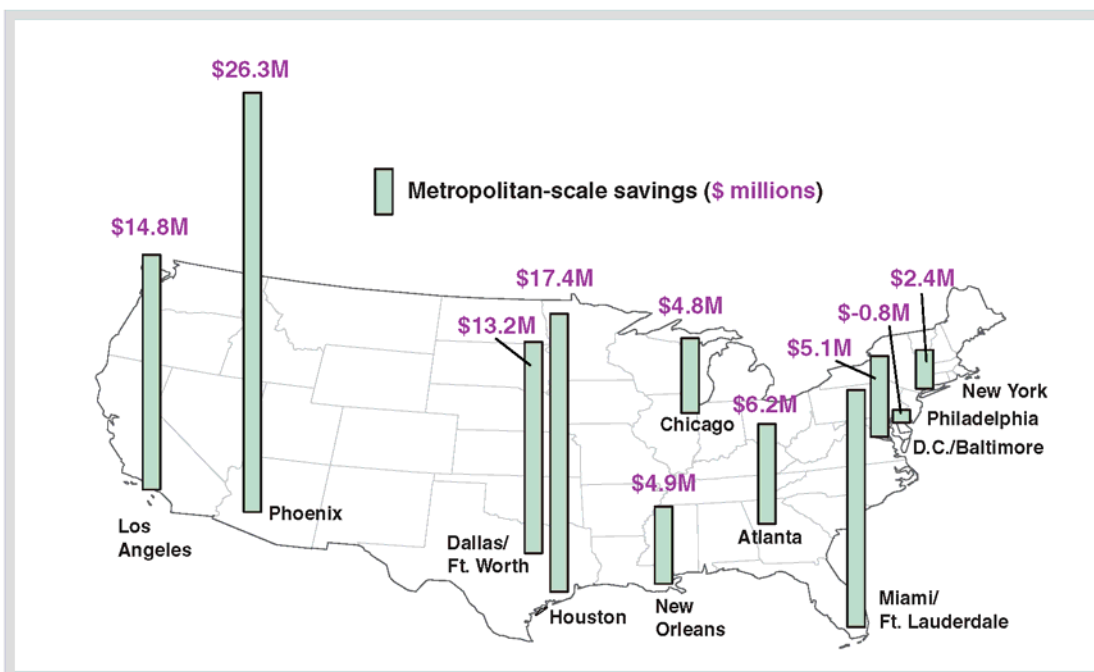


Figure EX-1. Potential annual cool roof net energy savings in U.S. cities.

The Need for Cool Color Roofing

Cool nonwhite roofing technology is intended not to replace light-colored roofing, but to improve the solar reflectance of dark-colored products, which dominate the residential roofing

market. (White residential roofing products stay cool in the sun, but sell poorly in California where homeowners prefer the aesthetics of dark-colored roofs.) Cool Color Roofing technology makes solar-reflective roofing available in any color (dark or light) by selectively reflecting the invisible component of sunlight in the “near-infrared” (NIR) spectrum (see Figure EX-2).

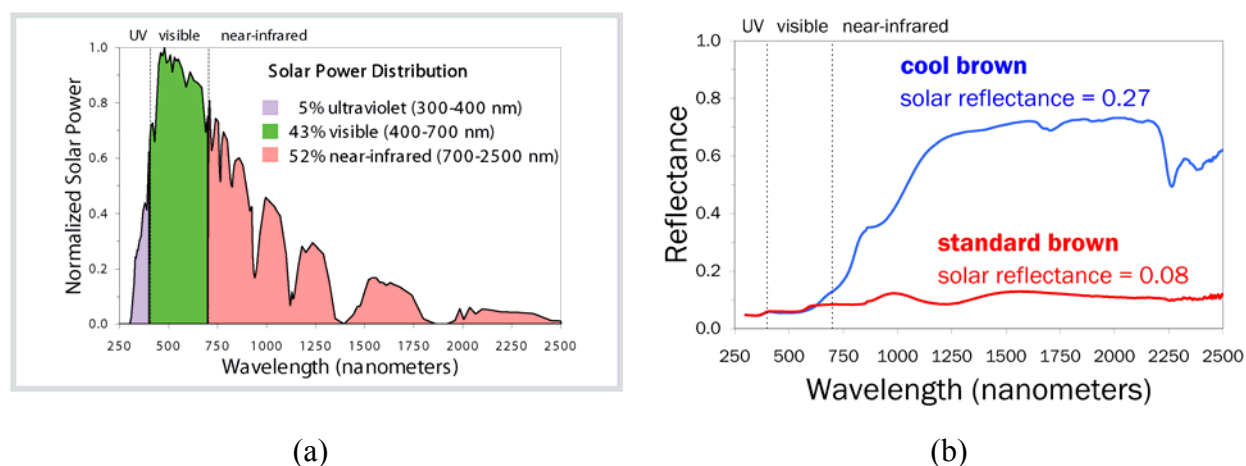


Figure EX-2. (a) Spectral solar power distribution, and (b) solar spectral reflectance of cool and standard brown surfaces.

On a summer day, the peak daily surface temperature of a cool dark roof of solar reflectance 0.35 is about 14 °C lower than that of a conventional dark roof of solar reflectance 0.10. Compared to the conventional dark roof, the cool dark roof conducts about 20 to 40 percent less heat into a home’s conditioned space, reducing the home’s demand for cooling power by about 7 to 15 percent in the late afternoon. These are the same hours during which demand for air conditioning strains the electrical grid and requires utilities to produce additional power using less efficient, more expensive, and more polluting “peak” generators. The cool dark roof yields a net annual energy savings (decrease in cooling energy minus increase in heating energy) of about 6 to 11 percent. . Our findings for sub-tile venting shows the heating penalty is lessened, which will make annual energy savings for cool roofs even more appealing.

Figure EX-3 depicts examples of cool metal panel, concrete tile, asphalt shingle, and clay tile roofing products.

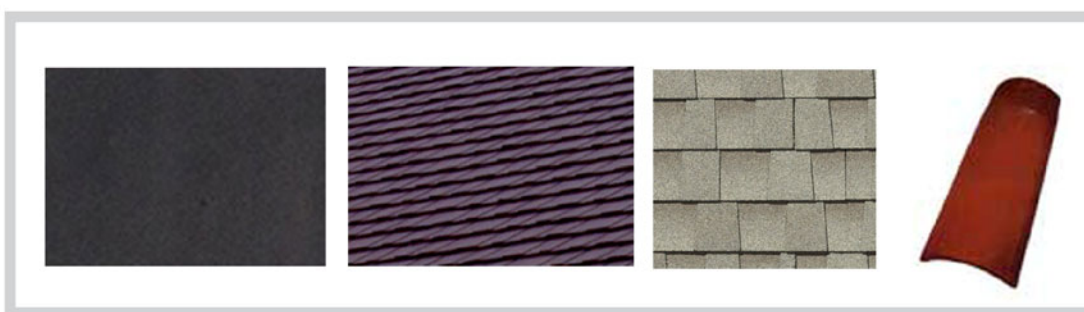


Figure EX-3. Cool metal panel, concrete tile, asphalt shingle, and clay tile roofing products.

Development of Cool Color Roofs

This multi-year research project is funded by the California Energy Commission's Public Interest Energy Research program, with an initial grant from the U.S. Department of Energy. The California Energy Commission's (the Commission) cool-color program at LBNL has three elements: (1) measuring the rates at which many common pigmented coatings absorb (convert to heat) and backscatter (reflect) light at wavelengths in the UV, visible, and NIR spectra; (2) using these rates in a LBNL software tool for the design of color-matched coatings with high solar reflectance; and (3) working with the roofing industry to develop novel manufacturing methods. Our industrial partners manufactured the prototypes and products. ORNL performed the demonstration work, measuring both the residential energy savings achieved by use of cool colored roofing, and the extent to which exposure changes the appearance and performance of cool colored roofing. ORNL also tested several cool roofing products at their facilities at Oak Ridge. Hereafter, we refer to this national labs partnership as the "Cool Team."

Pigment characterization begins with measuring the reflectance (r) and transmittance (t) of a thin coating (e.g., a paint film) colored by single pigment, such as iron oxide red. These "spectral," or wavelength-dependent, properties of the pigmented coating are measured at 441 evenly spaced wavelengths spanning the solar spectrum (300 to 2500 nanometers (nm), where $1\text{ nm} = 10^{-9}$ meter.) Inspection of the film's spectral absorptance (calculated as $1-r-t$) reveals whether a pigmented coating is "cool" (has low NIR absorptance) or "hot" (has high NIR absorptance).

The spectral reflectance and transmittance measurements are used to compute spectral rates of light absorption and backscattering (reflection) per unit depth of film. These calculations employ a variant of the Kubelka-Munk two-flux continuum model of light propagation through a pigmented coating that Berkeley Lab has adapted to account for the reflectance of incompletely diffused light at the air-coating interface. Such "interface reflectances" can significantly alter the reflectance and transmittance of the optically thin pigmented coatings applied to roofing materials.

To help the roofing industry identify cool pigments to use and hot pigments to avoid in their coatings, the LBNL researchers have produced a browsable HTML database describing the solar spectral optical properties of more than 80 single-colorant pigmented coatings (see Figure EX-4). The database charts the solar spectral reflectance, transmittance, absorptance, backscattering coefficient, and absorption coefficient of each pigmented coating, and also presents images, commentary, and a chemical description of each pigment. Machine-readable datafiles are also included.

[R03] Red Iron Oxide (iii)

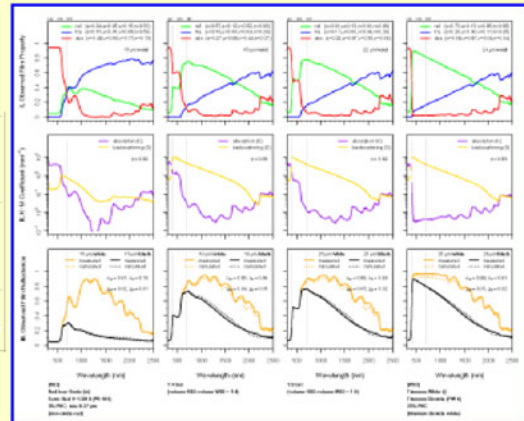
Paint Code	R03
Paint Name	Red Iron Oxide (iii)
Pigment Name	Ferro Red V-13810 (PR 101)
Color Family	Red/Orange
Color Subfamily	iron oxide red
Mean Particle Size (microns)	0.27
Dry Film PVC	3%
Pigment Datasheet	available
Paint Datasheet	unavailable
LBNL Commentary	available

Masstone and Mixtures with White (Tints)

[\[R03\] Red Iron Oxide \(iii\)](#) +
[\[W03\] Titanium White \(i\)](#)

image over white				
image over black				
spectral datafile	R03 masstone	R03 tint 1:4	R03 tint 1:9	W03 masstone

[guide to reading spectral datafiles](#)



Mixtures with Nonwhite Colors

[\[R03\] Red Iron Oxide \(iii\)](#) +
[\[B16\] Iron Titanium Brown Spinel \(i\)](#)

image over white			
image over black			
spectral datafile	R03 masstone	R03+B16 mixture 1:1	B16 masstone

[guide to reading spectral datafiles](#)

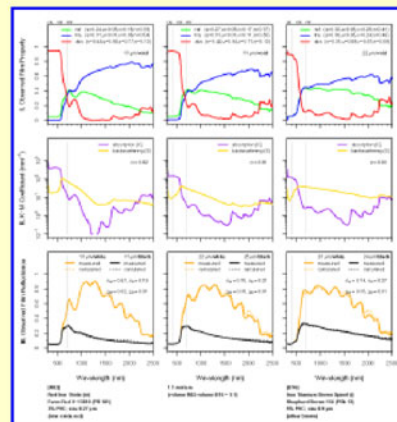


Figure EX-4. A screen image of the cool coatings database.

The radiative properties of these pigmented coatings serve as inputs to Pinwheel™, a software tool for the design of color-matched cool coatings that the LBNL team has developed and shared with its industrial partners (see Figure EX-5).

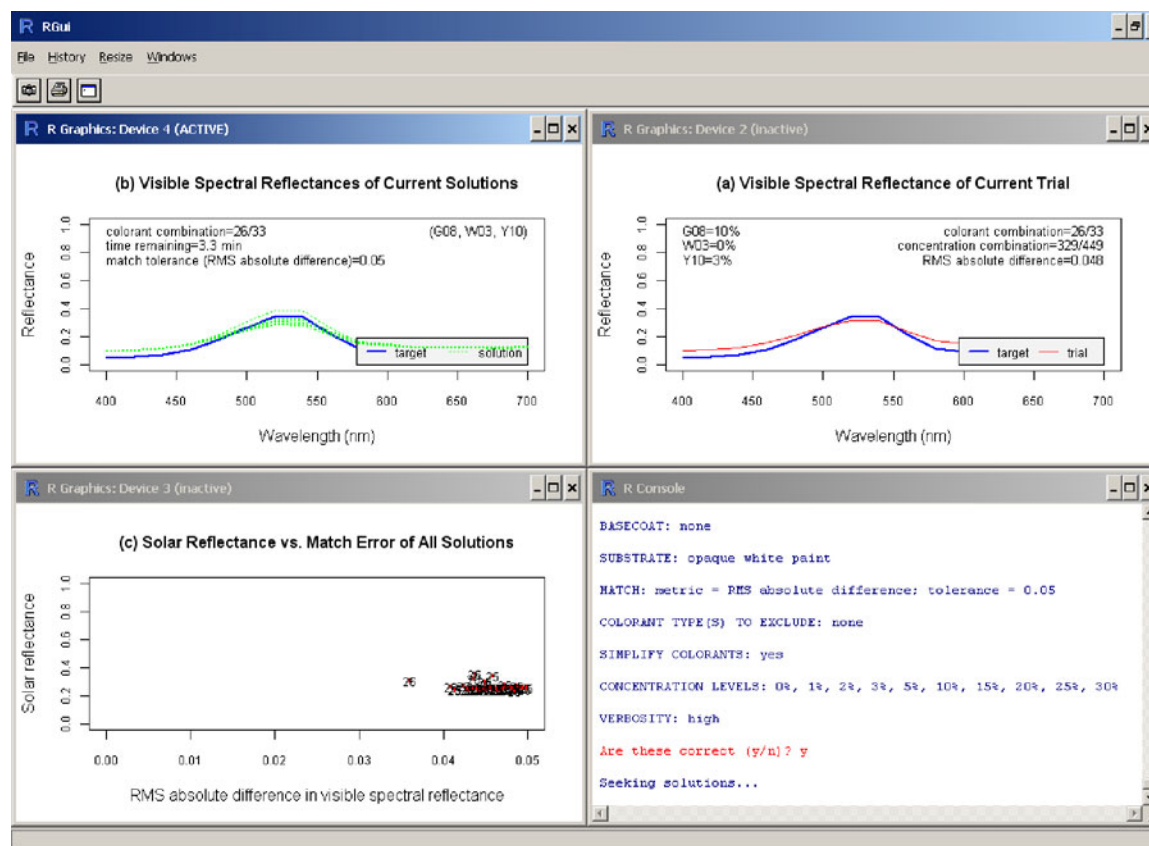


Figure EX-5. Pinwheel™ screen shot.

Pinwheel™ formulates color-matched coatings with high solar reflectance. It models a coated surface with two or three layers: an opaque substrate, an optional basecoat, and a topcoat. The solar spectral reflectance of the substrate; the thickness and colorant composition of the optional basecoat; and the thickness of the topcoat are specified by the coating designer. Pinwheel™ then seeks the topcoat colorant composition that maximizes the solar reflectance of the coated surface while acceptably matching a target visible spectral reflectance. The solar spectral reflectance of a coated surface, and hence its solar reflectance and visible spectral reflectance, are computed by applying to the solar spectral absorption and backscattering coefficients of colorants (a) a two-flux, two-constant model of light propagation through a film and (b) a colorant mixture model. Pinwheel™ has a large library of over 80 colorants whose solar spectral properties have been characterized by LBNL.

This tool differs in three major respects from conventional coating formulation software. First, it predicts solar spectral reflectance (300 to 2500 nm), rather than just visible spectral reflectance (400 to 700 nm). Second, it does not require that coatings be opaque. This permits design of thin coatings that transmit both visible and near-infrared light, as well as thicker coatings that stop visible light but transmit near-infrared light. Third, it contains the solar (and not just visible) spectral properties of the 80+ colorants.

Production of Cool Colored Roofing

Asphalt shingles are the dominant residential roofing product in the western United States, covering about 54% of the total residential roof area. The other major residential roofing products are concrete tiles (10%), clay tiles (10%), metal panels (9%), and wood shake (4%). The Cool Team and their industrial partners have developed methods for creating cool colored surfaces and applied them to create a wide variety of residential roofing materials, including metal, clay tile, concrete tile, and asphalt shingle. The basic technique is to maximize NIR reflectance by coloring a topcoat with pigments that weakly absorb and (optionally) strongly backscatter NIR radiation, and adding an NIR-reflective basecoat (e.g., titanium dioxide white) if both the topcoat and the substrate weakly reflect NIR radiation. Use of NIR-absorbing pigments (e.g., carbon black) commonly used to adjust colors must be minimized. LBNL's coating design software guides the formulation of the topcoat and optional basecoat.

The Cool Team collaborated with pigment manufacturers and roofing materials manufacturers. The materials companies are:

- 3M Industrial Minerals (St. Paul, MN);
- Akzo Nobel (Macungie, PA);
- American Rooftile Coatings (Fullerton, CA);
- BASF Industrial Coatings (Southfield, MI);
- CertainTeed Corporation (Valley Forge, PA);
- Custom-Bilt Metals (Chino, CA);
- Elk Corporation (Ennis, TX);
- GAF Materials (Wayne, NJ);
- Hanson Roof Tile (Fontana, CA);
- ISP Minerals (Hagerstown, MD);
- MCA Clay Tile (Corona, CA);
- Monier Lifetile (Thousand Oaks, CA);
- Owens Corning (Granville, OH);
- Steelscape Inc. (Kalama, WA).

The pigment manufacturers are Ferro Corporation (Cleveland, OH) and Shepherd Color Company (Cincinnati, OH).

All of these companies have introduced, or plan to introduce, cool color roof products or components (e.g., pigments, coatings, or colored granules). This consortium includes most of the major roofing manufacturers in the United States. Therefore, the appropriate product comparison is between a manufacturer's conventional roofing product, and its corresponding Cool Color Roofing product.

Metal panels and clay tiles were the first types of roofing to be produced in cool colors. BASF Industrial Coatings (Southfield, MI) has launched "Superl SP II™ ULTRA-Cool®," a line of cool colored Kynar coatings that is quickly replacing the more conventional silicone-modified polyester coatings. Steelscape Inc. (Kalama, WA) has recently introduced Spectrascape MBM, a cool Kynar coating for the metal building industry. Custom-Bilt Metals (Chino, CA) has switched over 250 of its metal roofing products to cool colors.

Clay tiles are colored with a pigmented glaze that is fired at high temperature. MCA Clay Tile (Corona, CA) is currently selling 11 products with solar reflectances exceeding the ENERGY STAR requirement of 0.25. The Berkeley Lab team is working with MCA tile to further increase the solar reflectance of its products by adding a white basecoat.

Concrete tiles can be colored either by mixing pigments into the wet concrete (cement + aggregate + water), or by adding a pigmented coating to the tile's surface. American Rooftile Coatings (Fullerton, CA) is currently selling polymeric coatings systems for concrete tiles that offer solar reflectances of at least 0.35.

Berkeley Lab has collaborated with a manufacturer of roofing granules (ISP Mineral Products; Hagerstown, MD) to develop about 100 prototype shingles. Figure EX-6 shows the iterative development of a cool black shingle prototype. A conventional black roof shingle has a reflectance of about 0.04. Replacing the granule's standard black pigment with a cool NIR-scattering black pigment (prototype 1) increases the solar reflectance of the shingle to 0.12. Incorporating a thin white sublayer (prototype 2) raises the shingle's solar reflectance to 0.16; using a thicker white sublayer (prototype 3) increases the shingle's reflectance to 0.18. The figure also shows an approximate performance limit (solar reflectance 0.25) obtained by applying 25-nm NIR-reflective black topcoat over an opaque white background. Roughness and limits to the thicknesses of the basecoat and topcoat are expected to make the reflectance of any granule-surfaced shingle pigmented with this cool inorganic black less than that achieved by the white-backed smooth film.

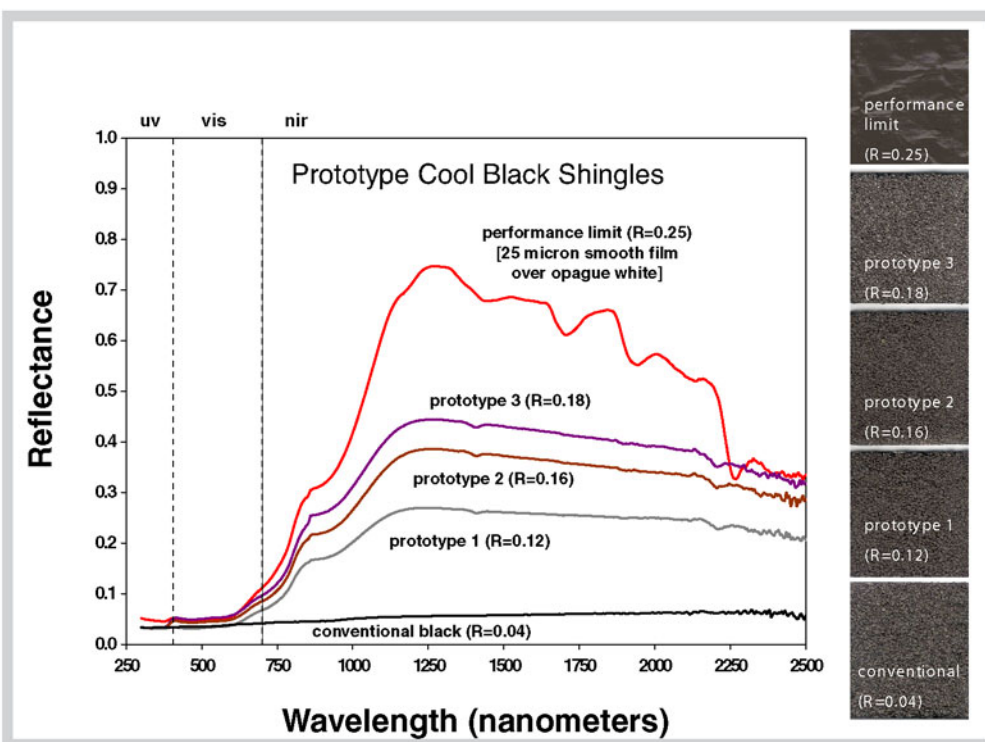


Figure EX-6. Development of a cool black shingle.

In 2005, one of the industrial partners, Elk Corporation (Ennis, TX) introduced its Prestique Cool Colors Series, a small line of light-gray and light-brown asphalt shingles with solar reflectances that meet or exceed the Energy Star requirement of 0.25. The cool color shingles are advertised

on Elk's web site¹ as the "first energy-efficient cool asphalt shingles offered in a palette of rich, organic colors." Elk offers a 40-year limited warranty with a limited wind warranty of up to 90 mph, and a UL Class "A" fire-rating. The prototype shingles were developed in conjunction with 3M™ to meet initial ENERGY STAR performance.

Field-Testing and Demonstration of Cool Colored Roofing

ORNL has set up a residential demonstration site in Fair Oaks, CA (near Sacramento) consisting of two pairs of single-family, detached houses roofed with metal and concrete tile. We have also set up two houses in Redding, CA to demonstrate asphalt shingles. The demonstration pairs each include one building roofed with a cool-pigmented product and a second building roofed with a conventionally (warmer) pigmented product of nearly the same color. The paired homes are adjacent, and share the same floor plan, roof orientation, level of blown ceiling insulation of 3.4 m²K/W (R-19 insulation), and all have air-handlers and air-delivery duct work in the attic. Demonstration homes in Fair Oaks have soffit and gable vents, while the homes in Redding are equipped with soffit and ridge vents. Each home will be monitored through at least the summer of 2006.

Temperatures at the roof surface, on the underside of the roof deck, in the mid-attic air, at the top of the insulation, on the surface of the sheet rock facing the attic, and inside the building are logged continuously by a data acquisition system. Relative humidity in the attic air and the residence are also measured. Heat flux transducers are embedded in the sloped roofs and the attic floor to measure the roof heat flows and the building heat leakage. We have instrumented the building to measure the total house and air-conditioner electrical energy use. A fully instrumented meteorological weather station is set up to collect the ambient dry bulb temperature, the relative humidity, the solar irradiance, and the wind speed and wind direction.

One of the Fair Oaks homes roofed with low-profile concrete tile was colored with a conventional chocolate brown coating (solar reflectance 0.10), while the other was colored with a matching cool chocolate brown with solar reflectance 0.41. The attic air temperature beneath the cool brown tile roof has been measured to be 3 to 5 K cooler than that below the conventional brown tile roof during a typical hot summer afternoon. The results for the pair of homes roofed with painted metal shakes are just as promising. There the attic air temperature beneath the cool brown metal shake roof (solar reflectance 0.31) was measured to be 5 to 7 K cooler than that below the conventional brown metal shake roof. Attic air temperature below the cool shingle (solar reflectance 0.26) was about 3 K cooler than the temperature below the conventional pigmented shingle roof.

The application of cool colored coatings reduced the surface temperature of the roofs, which in turn reduced the average daylight heat flows crossing the roof deck by 20% for cool pigmented tile, by 32% for cool pigmented painted metal shakes and by 30% for cool pigmented asphalt shingle roofs as compared to each roof type's conventional counterpart. A day selected from August 2004 depicts a consistent and sustained reduction in heat flow during the daylight hours for the painted metal roof shakes (see Figure EX-7).

Cool color materials appeared to provide more thermal benefit for the pair of homes with metal roofs than the pair of homes with tile roofs. We believe the difference is attributable to sub-tile

¹ http://www.elkcorp.com/homeowners/products/shingles_prestique_ccs.cfm

venting of the concrete tile roofs as compared to the metal shake roofs which were direct nailed to the roof deck. Sub-tile venting is more efficient on hotter roofs so it diminishes the effect of the solar reflectance of the cool tiles.

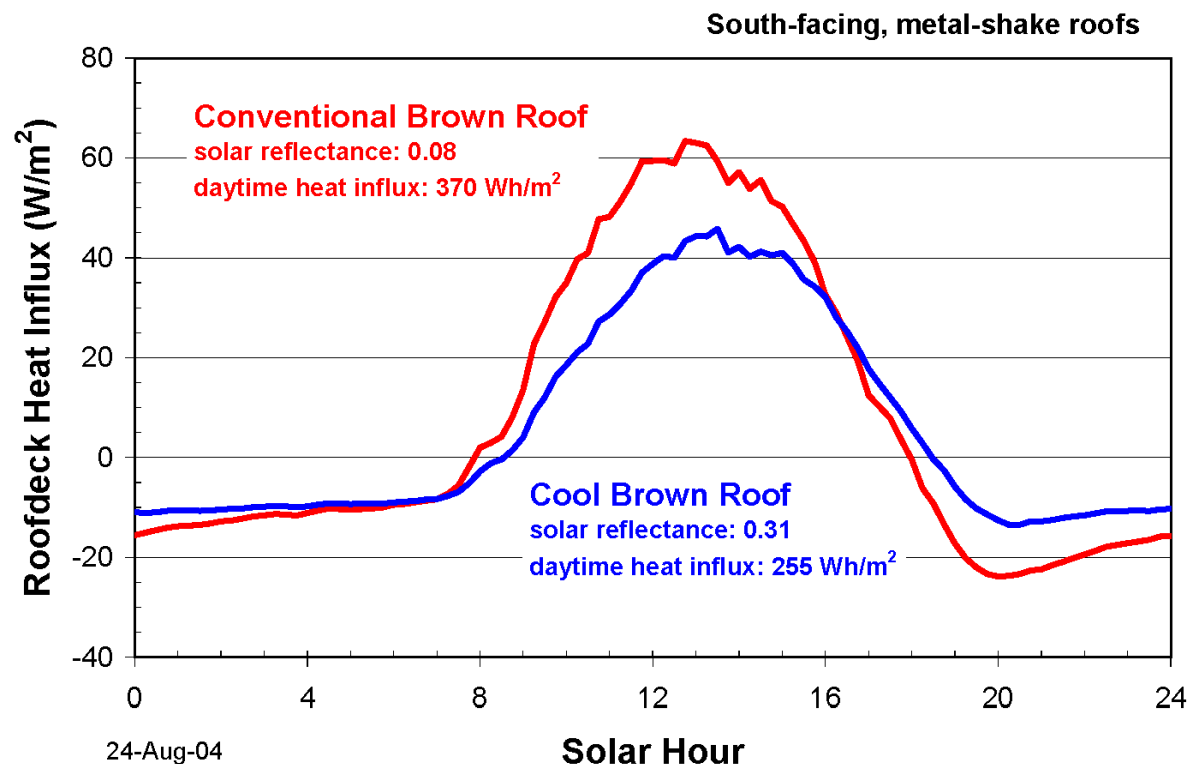


Figure EX-7. Heat flows through the roof decks of an adjacent pair of homes over the course of a hot summer day. The total daily heat influx through the cool brown metal shake roof (solar reflectance 0.31) between the solar hours of 8AM and 5PM is 31% lower than that through the conventional brown metal shake roof (solar reflectance 0.08).

Materials Testing at Weathering Farms in California

The long-term benefits of cool pigmented roofing systems (Akbari et al. 2004) can be compromised if a significant loss in solar reflectance occurs during the first few years of service life. Ultraviolet radiation, atmospheric pollution, microbial growths, acid rain, temperature cycling caused by sunlight and sudden thunderstorms, moisture penetration, condensation, wind, hail, freezing, and thawing are all thought to contribute to the loss of a roof's solar reflectance. Understanding the effect of climatic soiling is essential for developing defensible claims about energy savings for cool roofs. Miller et al. (2002) discovered that aerosol deposition introduced biomass of complex microbial consortia onto the test roofs and the combination of contaminants and biomass accelerated the loss of solar reflectance for the thermoplastic membranes and the roof coatings. Results published by Berdahl et al. (2002) indicate that the "the long-term change of solar reflectance appears to be determined by the ability of elemental carbon (deposited soot) to adhere to the roof, resisting washout by rain".

To document the effect of airborne contaminants and biomass we completed the following objectives (1) set up seven weathering sites in six climatic zones of California; (2) measured the drop in solar reflectance and the change in thermal emittance of roof products with and without cool pigmented colors; (3) characterized the particulate matter deposited on the roof samples; (4) established the relationship between deposited contaminants and the loss of solar reflectance; (5) determined the contribution of particulate matter on the enhancement or loss of solar reflectance; (6) identified the biomass existing on roof samples; and (7) determined the effect of biomass on the loss of solar reflectance.

The long-term loss of reflectance appears driven by the ability of the particulate matter to cling to the roof and resist being washed off by wind and or rain. The chemical composition of particles deposited on the roof samples was very similar across the state of CA; there was no clear distinction from one region to another. Organic and elemental carbon was detected; however, the elemental carbon did not contribute significantly to the loss of solar reflectance. Dust particles (characterized by Ca and Fe) and organic carbon compensated for the loss of solar reflectance due to elemental carbon possibly because some crystalline forms of these elements were light reflecting and contributed to the solar reflectance. Polar lipid fatty acid and quinone analyses showed diverse microbial communities with cyanobacteria or fungi being the dominant players.

Climatic soiling did not cause the cool pigmented roof coupons to lose any more solar reflectance than their conventional pigmented counterparts. The loss in solar reflectance for painted metal and clay and concrete tile coupons was of the order 6% of the initial reflectance for this 2½ year time limited study. As an example, the solar reflectance of a cool brick-red colored metal dropped from 0.37 to 0.36; only a 0.02 drop over 2 ½ years. Results show that elemental or black carbon did not contribute significantly to the degradation of reflectance, but dust particles (characterized by Al) and organic carbon had a statistically significant effect on balancing the degradation over the course of the study.

Steep-slope Assembly Testing at ORNL

An assembly of steep-slope attics having shed-type roofs was installed on top of the ESRA for field-testing clay and concrete tile roofs. The attics are adjacent to one another, and their shed roofs face directly south. The footprint for each attic is about 16 ft long by 5 ft wide. Roof slope was set at 4 in. of rise for every 12 in. of run (18.4° pitch). Soffit and ridge venting are provided with vent openings of 1:300. The steep-slope assembly was field-tested for a summer with the ridge vent closed to simulate conventional construction in the western states and with the ridge vent open the following summer to observe whether an unimpeded airflow under the tile (sub-tile venting) and attic ventilation would further improve the thermal performance of the tile roofs.

A high-profile S-Mission clay tile with cool pigmented colors, two different styles of high-profile terra-cotta concrete tiles, a medium-profile concrete (the same as that tested in California demonstrations), and a flat concrete slate tile were installed on the attic assemblies by the Tile Roofing Institute. The clay S-Mission tile and the medium-profile concrete tile were direct-nailed to the roof deck, a high-profile S-Mission concrete tile was spot-adhered with foam to the roof deck, the flat concrete slate tile was fastened to a batten and counter-batten system, and another concrete S-Mission tile was fastened to battens. A sixth attic assembly has a conventional asphalt shingle roof for comparing roof and ceiling heat flows.

Cool color pigments and sub-tile venting of clay and concrete tile roofs significantly impacted the heat flow crossing the roof deck. Field measures for the tile roofs revealed a 70% drop in the peak heat flow crossing the deck as compared to a direct-nailed asphalt shingle roof. The slate and medium-profile concrete roofs, having nearly the same surface properties as the asphalt shingle, reduced the deck heat flow by ~45% of that crossing the shingle roof because of sub-tile venting. The results imply that sub-tile venting is just as important as is the boost in solar reflectance for reducing the heat gain into the conditioned space.

In winter, the air gap on the tile's underside adds an additional radiation heat transfer resistance which causes the heat escaping the roof decks to be about the same as that observed for the direct nailed asphalt shingles in East Tennessee's climate. Sub-tile venting therefore lessens the heating penalty associated with cool roof products. The improved summer performance coupled with the reduced heat losses during the winter as compared to a dark heat absorbing shingle roof show that offset-mounting roofs can provide the roof industry the opportunity to market cool pigmented roofs in climates that are predominated more by heating loads. Sub-tile venting and cool pigments provide the best of both worlds; reduced cooling loads in summer and reduced heat loads in winter.

Accelerated Weathering and Product Useful Life

The Cool Team studied several aspects of the weathering of roofing materials. Xenon-arc and fluorescent light exposures were conducted to judge the effectiveness of cool pigments used in painted metal, clay tile, concrete tile and asphalt shingle roof products. Test results were very promising and showed that new cool pigmented concrete, clay, painted metal and asphalt shingle roofs maintain their solar reflectance as well as their standard production counterparts. Total color change is reduced or at least similar and the new cool pigmented products have similar if not improved fade resistance and gloss retention.

Degradation of materials initiated by ultraviolet radiation was investigated for plastics used in roofing, as well as wood and asphalt. Elevated temperatures accelerate many deleterious chemical reactions and hasten diffusion of material components. Effects of moisture include decay of wood, acceleration of corrosion of metals, staining of clay, and freeze-thaw damage. Soiling of roofing materials causes objectionable stains and reduces the solar reflectance of reflective materials. (Soiling of non-reflective materials can also increase solar reflectance.) Soiling can be attributed to biological growth (e.g., cyanobacteria, fungi, algae); deposits of organic and mineral particles; and to the accumulation of fly ash, hydrocarbons and soot from combustion.

Technology transfer

The objective of this task was to make cool-colored roofing materials available for the residential market within three to five years. LBNL, ORNL, color pigment manufacturers and granule manufacturers worked and supported the efforts of roofing manufacturers to penetrate the roofing market with new, more reflective cool-pigmented colored roofing materials. The Cool Team worked with roofing component manufacturers and color pigment manufacturers to introduce prototype cool-colored asphalt shingles, clay and concrete tiles, metal roofing, and wood shake roof products. Both laboratories in conjunction with their respective industry partners presented research results at appropriate trade shows, and published their results in each

industry's appropriate trade magazine. The following is a list of articles presented in various trade magazines, conferences, and academic journals.

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Levinson, R. P. Berdahl, H. Akbari, W. Miller, I. Joedicke, J. Reilly, Y. Suzuki, M. Vondran. 2005. "Methods of Creating Solar-Reflective Nonwhite Surfaces and their Application to Residential Roofing Materials." <i>Solar Energy Materials & Solar Cells</i> (in press).
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Levinson, R., P. Berdahl and H. Akbari. 2005. "Solar spectral optical properties of pigments, part II: Survey of common colorants." <i>Solar Energy Materials & Solar Cells</i> , Vol 89/4 pp 351-389, 2005.
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Levinson, R., H. Akbari and J. Reilly. 2004. Cooler tile-roofed buildings with near-infrared-reflective nonwhite coatings. Accepted by <i>Building & Environment</i> .
Miller, W.A., MacDonald, W.M., Desjarlais, A.O., Atchley, J.A., Keyhani, M., Olson, R., Vandewater, J. 2005. "Experimental analysis of the natural convection effects observed within the closed cavity of tile roofs." Proceedings of Cool Roofing ... Cutting through the Glare, Atlanta GA, May 12-13, RCI Foundation.
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The Energy Commission through this project has dramatically advanced the technology of non-white "Cool Roofs" that exploit complex inorganic paint pigments to boost the solar reflectance of clay and concrete tile, painted metal, and asphalt shingle roofing. The project has successfully developed several non-white cool-colored roof products for sloped roofs over the past three years and has shown positive energy savings in residential field tests demonstrating pairs of homes roofed in concrete tile, painted metal and asphalt shingles with and without cool pigmented materials. Without further efforts, the accomplishments achieved by the Energy Commission in its "Cool Roofs" Public Interest Energy Research (PIER) project will creep into the marketplace over the next several decades, slowly bringing the significant energy, cost, smog and carbon savings that the technology promises.

Near the end of this project, the project's 16 industrial partners discussed their needs to further develop and successfully market their residential cool roofing products. The opportunity exists to rapidly accelerate the uptake of cool roofing materials. First and foremost, residential cool roofs need to be credited and recommended in the state's Title 24 standards that primarily determine what products are used in the construction of new houses and major remodels. Second, more cool materials for all residential (and commercial) sloped roofing systems must be available and appropriately labeled. Third, the application of appropriate labels on roofing products must

become universal. Fourth, architects, designers, builders, roofing material distributors and retailers, and consumers need to learn of the availability and benefits of using cool roofing materials. Fourth, California utilities and the state government can further influence the selection of cool roofs through innovative incentive and rebate programs to accelerate their market penetration. Finally, market penetration can also be accelerated by enhancing the credibility of retailer and utility marketing claims through large-scale demonstrations of cool roofs to consumers, developer, designers, and roofing contractors.

In collaboration with the roofing industry partners, we prepared a market plan for industry/national labs collaborative efforts to help the Energy Commission in deploying cool-colored roofing. The plan focuses on six parallel initiatives: 1) regulate; 2) increase product selection; 3) label, 4) educate; 5) provide incentives; and 6) demonstrate performance.

The Cool Team prepared a preliminary document of energy and peak demand savings for installing cool roofs in various California climates. This data can be further developed to prepare a proposal for updating the Title 24 to include cool colored roofing materials.

To estimate the energy-savings of cool-colored roofing materials, we calculated the annual cooling energy use of a prototypical house for most cooling dominant cities around the world. We used a simplified model that correlates the cool energy savings to annual cooling degree days (base 18°C) (CDD18). The model is developed by regression of simulated cooling energy use against CDD18. We performed parametric analysis and simulated the cooling- and heating-energy use of a prototypical house with varying level of roof insulation (R-0 to R-49) and roof reflectance (0.05 to 0.80) in more than 250 climate regions, using the DOE-2 building energy use simulation program.

We estimated of savings for a prototypical house for an increase in roof solar reflectance from a typical dark roof of 0.10 to a cool-colored roof of 0.40. The savings ranged from approximately 250 kWh per year for mild climates to over 1000 kWh per year for very hot climates. For houses that are not air conditioned, cool-colored roofing materials offer comfort, typically at very reasonable costs.

Performance Comparison of Cool Colored and Standard Roofs: Energy Savings and Environmental Benefits

For illustration purposes, we compared the attributes of cool-colored and standard roofing products. In the following matrix (Table EX-1), a conventional roof product is paired with a cool roof product from the same company. Four types of roof products are depicted in the matrix. The cool roof product is in light blue, the conventional product in red. Only the solar reflectance of the cool and conventional products are compared; all other rows enumerate the energy, power or money saved by the cool roof as compared to a conventional roof.

Table EX-1. A comparison of the attributes of cool-colored and standard roofing products.

Feature	Glazed clay tile roofing	Polymer-coated concrete tile roofing	Polymer-coated metal roofing	Asphalt shingle roofing with ceramic-coated granules	Competitive Advantage of Energy-Efficient Cool Color Roofing
Example of conventional roofing product (manufacturer/model/color name)	MCA Clay Tile/Corona Tapered Mission/Burnt Sienna	American Rooftile Coatings/ Wearn Earthtone Rooftile Coating / Onyx	Custom-Bilt Metals/Titan Select Vail Shingle/ Musket Brown	Elk/ Prestique Plus High Definition/ Weatherwood	
Example of cool roofing product (manufacturer/model/color)	MCA Clay Tile/Corona Tapered Mission/Tobacco	American Rooftile Coatings/ COOLTILE IR COATING™/ IR Onyx topcoat over Plaster White basecoat	Custom-Bilt Metals/Titan Cool Roof Vail Shingle /Musket Brown	Elk/ Prestique Cool Color Series/Cool Weatherwood	
Solar reflectance of conventional roofing product sample	0.18	0.04	0.08	0.09	
Solar reflectance of cool roofing product sample	0.37	0.38	0.27	0.25	
Solar reflectance increase (cool product reflectance – conventional product reflectance) for dark colors	0.18-0.25	0.18-0.34	0.17-0.25	0.10-0.16	Cool roofs absorb less solar heat
Reduction in peak surface temperature on a summer afternoon of the cool roof (K)	10-12	10-12	10-12	7-8	Cool roofs stay cooler in the sun, reducing urban air temperatures and slowing smog formation
Peak power demand savings of the cool roof (W)	300-400	300-400	400-600	300-350	Cool roofs help stabilize the electrical grid
Annual cooling energy savings of the cool roof (kWh)	150-400	150-400	250 - 650	190 - 490	Cool roofs save energy
Annual cooling energy savings at \$0.15/kWh of the cool roof (\$)	22 - 60	22 - 60	37 - 97	28 - 73	Cool roofs save money on air conditioning bills
Annual heating energy penalty of the cool roof (therms)	1 - 4	1 - 4	2 - 8	1 - 5	Heat lost in the winter from reflected incident solar gain is small compared to energy savings in the summer
Annual heating energy penalty at	2 - 6	2 - 6	3 - 12	2 - 7	Cost of heat lost in the winter

\$1.5/therm of the cool roof(\$)						from reflected incident solar gain is less than 30% of the cooling savings
Net savings provided by the cool roof(\$)	20 -54	20 – 54	35 - 85	26 - 66		Cool roofs reduce annual energy bill
Cost premium of the cool roof compared with conventional roof (\$)	nil	100 - 500	nil	500		Cost premium of cool roofs is small or nonexistent for most materials.
15-year net present value of net energy savings at 3% discount (\$)	240 - 650	240 - 650	420 - 1020	310 - 790		The energy savings of a cool roof is about 20 to 30 percent of the material cost of the cool roof.
Simple payback time of the cool roof (years)	0	2 - 10	0	8-19		Most cool roofs achieve payback quickly. New product introductions will reduce cool shingle roof payback.

* A dark-colored surface is defined here to mean one that reflects no more than 20% of *visible* sunlight. Smooth, flat surfaces reflect about 5% of visible sunlight when black; about 10% when dark brown; and about 10 to 20 % when dark red, dark green, or dark blue surfaces.

The cool color pigment database, Pinwheel™ coating design software, and engineering methods for producing cool surfaces help roofing material manufacturers develop cool color roofing products similar in appearance to their conventional products. The major selling point of cool products is that they keep roofs cooler, and therefore save customers money on air conditioning bills. In large areas of the United States with hot summertime climates, the energy savings from these cool roofs can be substantial (10 to 20 percent). Cool roofs also improve the comfort of the indoor environment by helping to maintain thermal comfort with less mechanical cooling. For some people, air conditioners are difficult to regulate to produce a comfortable temperature. Cool roofs also offer the added societal benefit of lowering peak power demand (relieving strain on the electricity grid) and reducing emissions of greenhouse gases and airborne pollutants from power plants (mitigating climate change and improving air quality).

Regional climate modeling suggests that the widespread application of cool roofs can reduce urban air temperatures, decreasing cooling peak power demand and smog production. For example, on a warm afternoon in Los Angeles, each 1°C decrease in the daily maximum temperature lowers peak demand for electric power by about 2 to 4 percent, and each 1°C decrease down to 21°C (70°F) reduces smog (specifically, the probability that the maximum concentration of ozone will exceed the California standard of 90 parts per billion) by 5 percent. A 3°C reduction in the air temperature of the Los Angeles basin could reduce peak power demand by 200 MW, offer cooling energy savings worth \$21 M/year, and yield a 12 percent reduction in ozone worth \$104 M/year [Rosenfeld et al. 1998]. More than 450 U.S. counties (including some of the most heavily populated areas of California) had ozone levels that exceeded federal 8-hour standards as of 2004. Widespread adoption of cool roofs could help cities in many of these areas reduce the magnitude of their air quality problem.

The principal application of Cool Color Roofing is to provide roofing manufacturers with the tools they need to develop energy-efficient products which (a) benefit their customers and (b) improve the competitive advantage of these U.S. roofing products in the marketplace. Cool color roofing materials provide clear, measured advantages and dollar savings compared to conventional roofing materials at a small cost premium that is paid back within a few years through reduced energy bills.

The cool color technologies have other applications:

Automobiles. The Berkeley team is now working with the automobile industry to apply cool colored coatings to the exterior metal and plastic surfaces of cars. Such coatings reduce the amount of solar heat absorbed by the car's body, lowering the air temperature in the cabin of a car that has been parked in the sun. This allows car manufacturers to install lighter, lower capacity air conditioning units that operate with greater efficiency. The reduced weight and power consumption of these AC units could increase the fuel efficiency of cars, potentially saving U.S. drivers billions of dollars in gasoline costs. This is a significant development given the current high cost of gasoline, and the security issues raised by dependence on foreign petroleum. Any inexpensive, easy-to-use technology that has the potential to save gasoline has a tremendous market potential.

Cool colors can also be applied to the interior surfaces of cars, such as seats and steering wheels, to lower their temperatures and make it more comfortable to enter and occupy a vehicle parked in the sun.

Buildings. Cool color pigments can be used in building paints to reduce solar heat gain by interior and exterior walls.

Clothing. Cool color pigments can be used in clothing to produce dark uniforms (such as those worn by police officers) that stay cool in the sun.

Miscellaneous. Cool color pigments can be used to reduce the sunlit temperature of a wide variety of coatings, including those applied to furniture, machinery, tools, or camping gear.

Concluding Comments

If we could develop technology to reduce every type of energy use by 10 to 20 percent, we would be taking a huge step towards reducing dependence on oil imports, and emissions of greenhouse gases. Energy-Efficient Cool Color Roofing accomplishes just this, while also strengthening the economy and improving air quality.

Re-roofing houses with cool products when roofs are due for replacement and specifying cool roofs in new construction are economically sensible ways to significantly increase energy efficiency. The price premium of cool roofs compared to conventional ones is small, and is paid back in air conditioning savings within a few years. When a sufficiently large number of home and commercial building owners adopt cool roofs regionally, urban air temperatures decrease, slowing the rate of smog formation. This improves public health, and helps cities meet federally mandated clean air requirements. Finally, cool roofs reduce peak electrical demand on hot summer afternoons, reducing strain on the electrical grid and helping to avoid blackouts and brownouts.

If applied to cars, cool color technology could improve fuel economy by allowing manufacturers to downsize air conditioning units. These savings could help further reduce greenhouse gas emissions and increase U.S. energy security by reducing reliance on imported petroleum. For all of these reasons Cool Colors, on roofs and in other applications, have a tremendous potential to contribute to the solution of major global problems within a short time, at a reasonable cost.

Recommendations

The California Energy Commission (CEC) has dramatically advanced the technology of non-white “Cool Roofs” that exploit complex inorganic paint pigments to boost the solar reflectance of clay and concrete tile, painted metal, and asphalt shingle roofing. The project has successfully developed several non-white cool-colored roof products for sloped roofs over the past three and a half years and has shown positive energy savings in residential field tests demonstrating pairs of homes roofed in concrete tile, painted metal and asphalt shingles with and without cool pigmented materials. Without further efforts, the accomplishments achieved by the CEC in its “Cool Roofs” Public Interest Energy Research (PIER) project will creep into the marketplace over the next several decades, slowly bringing the significant energy, cost, smog and carbon savings that the technology promises.

Near the end of the CEC project, the project's 16 industrial partners discussed their needs to further develop and successfully market their residential cool roofing products. Their recommendations and requests are summarized in Table EX-2.

The opportunity exists to rapidly accelerate the uptake of cool roofing materials. First and foremost, residential cool roofs need to be credited and recommended in the state's Title 24

standards that primarily determine what products are used in the construction of new houses and major remodels. Second, more cool materials for all residential (and commercial) sloped roofing systems must be available and appropriately labeled. Third, the cool roofing pigment database should be maintained and expanded with new materials in order to assist the industry to develop new and advanced materials at competitive prices. Fourth, the aging and weathering of cool roofing materials and their effects on the useful life of roofs need to be further studied. Fifth, the application of appropriate labels on roofing products must become universal. Sixth, architects, designers, builders, roofing material distributors and retailers, and consumers need to learn of the availability and benefits of using cool roofing materials. Seventh, California utilities and the state government can further influence the selection of cool roofs through innovative incentive and rebate programs to accelerate their market penetration. Eighth, for utilities to develop incentive programs and for manufacturers to coordinate their materials development with their marketing efforts, they need to have an industry-consensus calculator to accurately estimate energy and peak demand of cool colored roofs. The calculator should account for both the cooling energy savings and potential heating energy penalties of cool roofs. Finally, market penetration can be accelerated by enhancing the credibility of retailer and utility marketing claims through large-scale demonstrations of cool roofs to consumers, developer, designers, and roofing contractors.

Table EX-2. Industry needs to successfully market their cool roof product

Assistance requested in marketing cool roofs	Industry partner requesting assistance
Continuing education for design-build firms, architects, utility consumers, construction professionals and homeowners integrated into seminars offered by the California Association of Building Energy Consultants (CABEC).	Steelscape, BASF, Custom-Bilt, Shepherd
Software to estimate the cooling energy savings and peak demand reduction achieved by installing cool roofs on specific buildings	Steelscape, BASF, Custom-Bilt, Ferro, Elk, ARC
Monitoring solar reflectance and color change of the materials installed at the California weathering sites	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Elk, ARC
Monitoring solar reflectance, color change, and thermal performance of materials at ORNL test facilities and the Sacramento test homes	Steelscape, BASF, Custom-Bilt, ISP, Elk, Ferro, ARC
Expanding the cool coating database	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Shepherd, 3M
Large-scale demonstration of cool roofs	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Elk, ARC
Predictive software for design of cool coatings	Steelscape, BASF, Custom-Bilt, ISP, Ferro, 3M
Research to increase reflectivity and reduce costs	ISP, Ferro, Elk, 3M, Shepherd, ARC
Tools to accurately measure solar reflectance	ISP, Elk, 3M, ARC
Calculations of weathering benefits of cool roofing	ISP
Identification of new materials and techniques	ISP, Ferro, 3M
Determination of the relationship between granule and ultimate shingle reflectances	3M
Acceleration of cool roof rating criteria by CRRC and Energy Star	3M

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Introduction

Coatings colored with conventional pigments tend to absorb the invisible “near-infrared” (NIR) radiation that bears more than half of the power in sunlight (Figure 1). Replacing conventional pigments with “cool” pigments that absorb less NIR radiation can yield similarly colored coatings with higher solar reflectance. These cool coatings lower roof surface temperature, which in turn reduces the need for cooling energy in conditioned buildings and makes unconditioned buildings more comfortable.

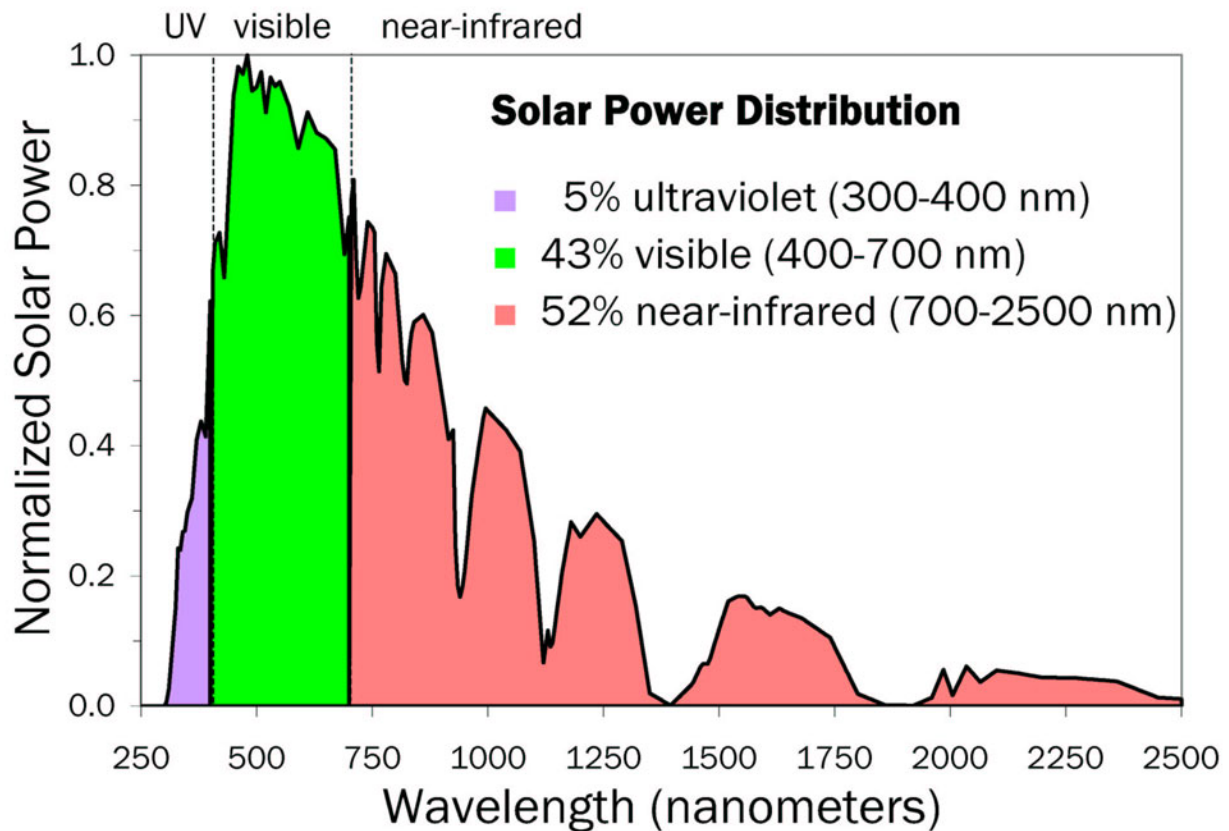


Figure 1. Peak-normalized solar spectral power; over half of all solar power arrives as invisible, “near-infrared” radiation

Field studies in California and Florida have demonstrated cooling-energy savings in excess of 20% upon raising the solar reflectance of a roof to 0.60 from a prior value of 0.10–0.20 (Konopacki and Akbari, 2001; Konopacki *et al.*, 1998; Parker *et al.*, 2002). Energy savings are particularly pronounced in older houses that have little or no attic insulation, especially if the attic contains the air distribution ducts. At 8¢/kWh, the value of U.S. potential nationwide net commercial and residential energy savings (cooling savings minus heating penalties) exceeds \$750 million per year (Akbari *et al.*, 1999). Cool roofs also significantly reduce peak electric

demand in summer (Akbari *et al.*, 1997; Levinson *et al.*, 2005a). The widespread installation of cool roofs can lower the ambient air temperature in a neighborhood or city, decreasing the need for air conditioning, retarding smog formation, and improving environmental comfort. These “indirect” benefits of reduced ambient air temperatures have roughly the same economic value as the direct energy savings (Rosenfeld *et al.*, 1998). Lower surface temperatures may also increase the lifetime of roofing products (particularly asphalt shingles), reducing replacement and disposal costs.

According to *Western Roofing Insulation and Siding* magazine (2002), the total value of the 2002 projected residential roofing market in 14 western U.S. states (AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, TX, UT, WA, and WY) was about \$3.6 billion (B). We estimate that 40% (\$1.4B) of that amount was spent in California. The lion’s share of residential roofing expenditure was for fiberglass shingle, which accounted for \$1.7B, or 47% of sales. Concrete and clay roof tiles made up \$0.95B (27%), while wood, metal, and slate roofing collectively represented another \$0.55B (15%). The value of all other roofing projects was about \$0.41B (11%). We estimate that the roofing market area distribution was 54–58% fiberglass shingle, 8–10% concrete tile, 8–10% clay tile, 7% metal, 3% wood shake, and 3% slate (Table 1).

Suitable cool *white* materials are available for most roofing products, with the notable exception (prior to March 2005²) of asphalt shingles. Cool nonwhite materials are needed for all types of roofing. Industry researchers have developed complex inorganic color pigments that are dark in color but highly reflective in the near infrared (NIR) portion of the solar spectrum. The high near-infrared reflectance of coatings formulated with these and other “cool” pigments—e.g., chromium oxide green, cobalt blue, phthalocyanine blue, Hansa yellow—can be exploited to manufacture roofing materials that reflect more sunlight than conventionally pigmented roofing products.

Cool colored roofing materials are expected to penetrate the roofing market within the next few years. Preliminary analysis suggests that they may cost up to \$1/m² more than conventionally colored roofing materials. However, this would raise the total cost of a new roof (material plus labor) by only 2 to 5%.

² In March 2005, a major manufacturer of roofing shingles in California announced availability of cool colored shingles in four popular colors.

Roofing Type	Market share by \$		Estimated market share by roofing area
	\$B	%	%
Fiberglass Shingle	1.70	47.2	53.6-57.5
Concrete Tile	0.50	13.8	8.4-10.4
Clay Tile	0.45	12.6	7.7-9.5
Wood Shingle/Shake	0.17	4.7	2.9-3.6
Metal/Architectural	0.21	5.9	6.7-7.2
Slate	0.17	4.7	2.9-3.6
Other	0.13	3.6	4.1-4.4
SBC Modified	0.08	2.1	2.4-2.6
APP Modified	0.07	1.9	2.2-2.3
Metal/Structural	0.07	1.9	2.2-2.3
Cementitious	0.04	1.1	1.2-1.3
Organic Shingles	0.02	0.5	0.6
Total	3.60	100	100

Table 1. Project residential roofing market in the U.S. western region surveyed by Western Roofing (2002). The 14 states included in the U.S. western region are AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, TX, UT, WA, and WY

In May 2002, the California Energy Commission (Energy Commission) sponsored a research project to develop “cool” nonwhite roofing products that could revolutionize the residential roofing industry. The technical project tasks included:

- Task 2.4: Development of Cool Colored Coatings
 - Task 2.4.1 Identify and Characterize Pigments with High Solar Reflectance
 - Task 2.4.2 Develop a Computer Program for Optimal Design of Cool Coatings
 - Task 2.4.3 Develop a Database of Cool-Colored Pigments
- Task 2.5 Development of Prototype Cool-Colored Roofing Materials
 - Task 2.5.1 Review of Roofing Materials Manufacturing Methods
 - Task 2.5.2 Design Innovative Methods for Application of Cool Coatings to Roofing Materials
 - Task 2.5.3 Accelerated Weathering Testing
- Task 2.6 Field-Testing and Product Useful Life Testing

Task 2.6.1	Building Energy-Use Measurements at California Demonstration Sites
Task 2.6.2	Materials Testing at Weathering Farms in California
Task 2.6.3	Steep-slope Assembly Testing at ORNL
Task 2.6.4	Product Useful Life Testing
Task 2.7	Technology transfer and market plan
Task 2.7.1	Technology Transfer
Task 2.7.2	Market Plan
Task 2.7.3	Title 24 Code Revisions

An initial collaboration between Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and eight roofing manufacturers rapidly grew to include 16 industrial partners (see Table 2). Seven other manufacturers and roofing organizations have joined the project’s advisory committee (see Table 3).

Our industry partners manufacture roofing materials, including fiberglass shingles, roofing granules, clay tiles, concrete tiles, tile coatings, metal panels, metal coatings, and pigments. The development work with our industrial partners has been iterative and has included selection of cool pigments, choice of base coats for the two-layer applications (discussed later in this report), and identification of pigments to avoid.

The Energy Commission’s goal is to create dark shingles with solar reflectances of at least 0.25, and other nonwhite roofing products—including tiles and painted metals—with solar reflectances not less than 0.40. Raising the solar reflectance of a residential roof from 0.15 (conventional dark color) to 0.40 (cool dark color) can decrease building cooling-energy use by more than 10%.

The manufacturing partners of the two national labs have raised the solar reflectance of commercially available concrete tile, clay tile, and metal roofing products to 0.30 – 0.45 from 0.05 – 0.25 by reformulating their pigmented coatings. Bilayer coating technology (a color topcoat over a white or other highly reflective undercoat) is expected to soon yield several cost-effective cool-colored shingle products with solar reflectances in excess of the Energy-Star[®] threshold of 0.25.

1.	3M Industrial Minerals, Pittsboro, NC; www.scotchgard.com/roofinggranules
2.	Akzo-Nobel, Macungie, PA; www.akzonobel.com
3.	American Rooftile Coatings, Fullerton, CA; www.americanrooftilecoatings.com
4.	BASF Industrial Coatings, Mount Olive, NJ; www.ultra-cool.basf.com
5.	CertainTeed, Valley Forge, PA; www.certainteed.com
6.	Custom-Bilt Metals, South El Monte, CA; www.custombiltmetals.com
7.	Elk Corporation, Dallas, TX; www.elkcorp.com
8.	Ferro Corporation, Cleveland, OH; www.ferro.com
9.	GAF Materials Corporation, Wayne, NJ; www.gaf.com
10.	Hanson Roof Tile, Fontana, CA; www.hansonrooftile.com
11.	ISP Minerals Incorporated, Hagerstown, MD; Tel. (301) 733-4000
12.	MCA Tile, Corona, CA; www.mca-tile.com
13.	MonierLifetile LLC, Irvine, CA; www.monierlifetile.com
14.	Owens Corning, Granville, OH; http://www.owenscorning.com/around/roofing/Roofhome.asp
15.	Shepherd Color Company, Cincinnati, OH; www.shepherdcolor.com
16.	Steelscape Incorporated, Kalama, WA; www.steelscape-inc.com

Table 2. List of industry partners

1.	DuPont Titanium Technologies
2.	National Roofing Contractors Association
3.	Cedar Shake and Shingle Bureau (CSSB)
4.	CRRC
5.	Cool Metal Roofing Coalition
6.	Tile Roofing Institute
7.	Asphalt Roofing Manufacturers Association

Table 3. Industry representation on the Project Advisory Committee

Technical Tasks

The following is a summary of the work accomplished under each task.

Task 2.4: Development of Cool Colored Coatings

To determine how to optimize the solar reflectance of a pigmented coating matching a particular color, and how the performance of cool-colored roofing products compares to those of a standard materials, we have (a) characterized the optical properties of over 80 single-pigment coatings; (b) created a database of pigment characteristics; and (c) developed a computer model to maximize the solar reflectance of roofing materials for a choice of visible color.

Task 2.4.1: Identify and Characterize Pigments with High Solar Reflectance

We examined pigments in widespread use, with particular emphasis on those that may be useful for formulating non-white materials that can reflect the near-infrared (NIR) portion of sunlight, such as the complex inorganic color pigments (mixed metal oxides).

Pigment characterization begins with measuring the reflectance r and transmittance t of a thin coating (e.g., a 25- μm thick paint film) colored by single pigment, such as iron oxide red. These “spectral,” or wavelength-dependent, properties of the pigmented coating are measured at 441 evenly spaced wavelengths spanning the solar spectrum (300 to 2500 nanometers). Inspection of the film's spectral absorbance (calculated as $1-r-t$) reveals whether a pigmented coating is “cool” (has low NIR absorbance) or “hot” (has high NIR absorbance).

The spectral reflectance and transmittance measurements are used to compute spectral rates of light absorption K and backscattering (reflection) S per unit depth of film. A cool color is defined by a small absorption coefficient K in the near infrared (NIR). For cool colors, the backscattering coefficient S is small (or large) in the visible spectral range for formulating dark (or light) colors, and preferably large in the NIR. (Weak backscattering in the NIR is acceptable when a basecoat or the substrate provide high NIR reflectance.) Calculations of S and K employ a variant of the Kubelka-Munk two-flux continuum model of light propagation through a pigmented coating that Berkeley Lab has adapted to account for the reflectance of incompletely diffused light at the air-coating interface. Such “interface reflectances” can significantly alter the reflectance and transmittance of the optically thin pigmented coatings applied to roofing materials.

As a check, we found that values of S computed from the Kubelka-Munk model for generic titanium dioxide (rutile) white pigment were in rough agreement with values computed from the Mie theory, supplemented by a simple multiple scattering model.

The optical properties of 87 single-pigment films—4 white, 21 black or brown, 14 blue or purple, 11 green, 9 red or orange, 14 yellow, and 14 pearlescent—were characterized by computing spectral Kubelka-Munk coefficients from spectral measurements of film reflectance and transmittance. Twenty-six polyvinylidene fluoride (PVDF) resin paint films were provided by a manufacturer of coil-coating paints. Another 34 acrylic paints were purchased as artist colors, and the remaining 27 coatings were acrylic-base letdowns (dilutions) of cool (primarily metal-oxide) pigment dispersions from pigment manufacturers.

We identified cool pigments in the white, yellow, black/brown, red/orange, blue/purple, and pearlescent color groupings with NIR thin-film absorptances less than 0.1, as well as other pigments in the black/brown, blue/purple, green, red/orange, yellow and pearlescent groupings with NIR absorptances less than 0.2. Most are NIR transmitting and require an NIR-reflecting background to form a cool coating. Over an opaque white background, some pigments in the pearlescent, white, yellow, black/brown red/orange, green, and blue/purple families offer NIR reflectances of at least 0.7, while other pigments in the blue/purple, black/brown, and green color families have NIR reflectances of at least 0.5. A few members of the white, yellow, black/brown, pearlescent, red/orange, and green color families have NIR scattering sufficiently strong to yield NIR reflectances of at least 0.3 (and up to 0.64) over a black background.

Use of pigments with NIR absorptances approaching unity (e.g., nonselective blacks) should be minimized in cool coatings, as might be the use of certain pearlescent, blue/purple, red/orange, and brown/black pigments with NIR absorptances exceeding 0.5.

Figure 2 illustrates our pigment characterization activities, showing (a) images over white and black backgrounds of the 87 single-pigment films; (b) coupons of a pigmented polymer film (an organic red) over white and black backgrounds; and (c) the measured and computed solar spectral reflectances of a pigmented polymer film (an inorganic cool black). The three charts show, from top to bottom, (i) measured reflectance, measured transmittance, and computed absorptance of a free film; (ii) Kubelka-Munk backscattering and absorption coefficients computed from the measured reflectance and transmittance of the free film; and (iii) the measured and computed reflectances of the film over black and white backgrounds, which are used to validate the accuracy of the backscattering and absorption coefficients computed from the free-film properties.

We have published two milestone papers published in the academic journal *Solar Energy Materials & Solar Cells* (Attachment 1). Feedback from the journal's referees was extremely positive. To wit:

REF#1: "Great work with extensive detail, I have not seen such detail on pigments since work in the 1960's by the aerospace companies. It is nice to see such a seminal work in one location and with one set of testing methodologies. Please publish."

REF#2: "...Very nice work, uniform and detailed- the beginnings of a handbook. Very valuable to my industry (paint formulation). If Elsevier puts together a Materials Property Handbook, the results of this work should be in it."

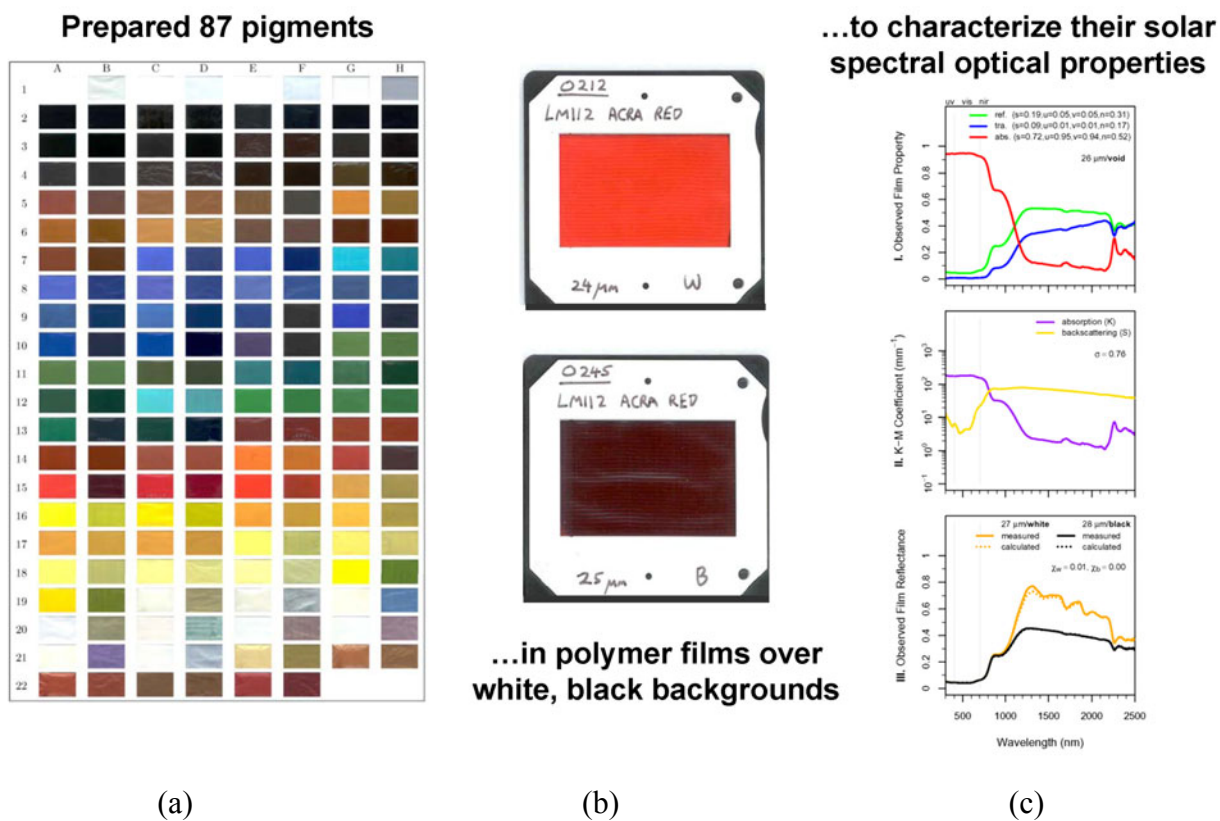


Figure 2. Illustration of our pigment characterization activities, showing (a) images over white and black backgrounds of the 87 characterized single-pigment coatings; (b) coupons of a pigmented polymer paint film (an organic red) over white and black backgrounds; and (c) measured and computed solar spectral optical properties of a characterized pigmented paint film (an inorganic black).

Task 2.4.2: Develop a Computer Program for Optimal Design of Cool Coatings

The radiative properties of the pigmented coatings characterized in Task 2.4.1 serve as inputs to Pinwheel™, a software tool for the design of color-matched cool coatings that the LBNL team has developed and shared with its industrial partners.

Pinwheel™ formulates color-matched coatings with high solar reflectance. It models a coated surface with two or three layers: an opaque substrate, an optional basecoat, and a topcoat. The solar spectral reflectance of the substrate; the thickness and colorant composition of the optional basecoat; and the thickness of the topcoat are specified by the coating designer. Pinwheel™ then seeks the topcoat colorant composition that maximizes the solar reflectance of the coated surface while acceptably matching a target visible spectral reflectance. The solar spectral reflectance of a coated surface, and hence its solar reflectance and visible spectral reflectance, are computed by applying to the solar spectral absorption and backscattering coefficients of colorants (a) a two-flux, two-constant model of light propagation through a film and (b) a colorant mixture model. Pinwheel™ has a large library of over 80 colorants whose solar spectral properties have been characterized by LBNL.

This tool differs in three major respects from conventional coating formulation software. First, it predicts solar spectral reflectance (300 to 2500 nm), rather than just visible spectral reflectance (400 to 700 nm). Second, it does not require that coatings be opaque. This permits design of thin coatings that transmit both visible and near-infrared light, as well as thicker coatings that stop visible light but transmit near-infrared light. Third, it contains the solar (and not just visible) spectral properties of the 80+ colorants.

Pinwheel™ executes in R, an interpreted programming environment available as free software for the Windows, Mac OS X, and Unix platforms. The following Pinwheel™ code designs a cool coating that matches a known color (“emerald green”) and combines up to three colorants:

```
design(  
  target="emerald-green",  
  topcoat.colorants=list("U08, G", "W", "Y01, Y10, Y14")  
)
```

The first colorant is to be chosen from the set “U08, G”, where “U08” is a particular blue and “G” can be any of 11 characterized green pigments. The second colorant is to be “W”, which represents any of four characterized white pigments. The third colorant is to be chosen from the set of three characterized yellow pigments “Y01, Y10, Y14”. Each colorant can be present in a volume concentration ranging (by default) from 0 to 30%. The allowable concentrations are among many specifiable parameters with default values.

Figure 3 shows Pinwheel™ seeking the three-colorant combination that will produce the coating with maximum solar reflectance that matches the desired target color to within an acceptable tolerance. Chart (a) shows the visible spectral reflectance achieved by a particular set of colorants in a certain vector of concentrations. Chart (b) shows the visible spectral reflectance of all acceptable solutions found with all concentration vectors of that particular set of colorants. Chart (c) shows the solar reflectance versus match error of all acceptable solutions. The text

window in the lower right corner shows some of the parameters used in the formulation of this coating.

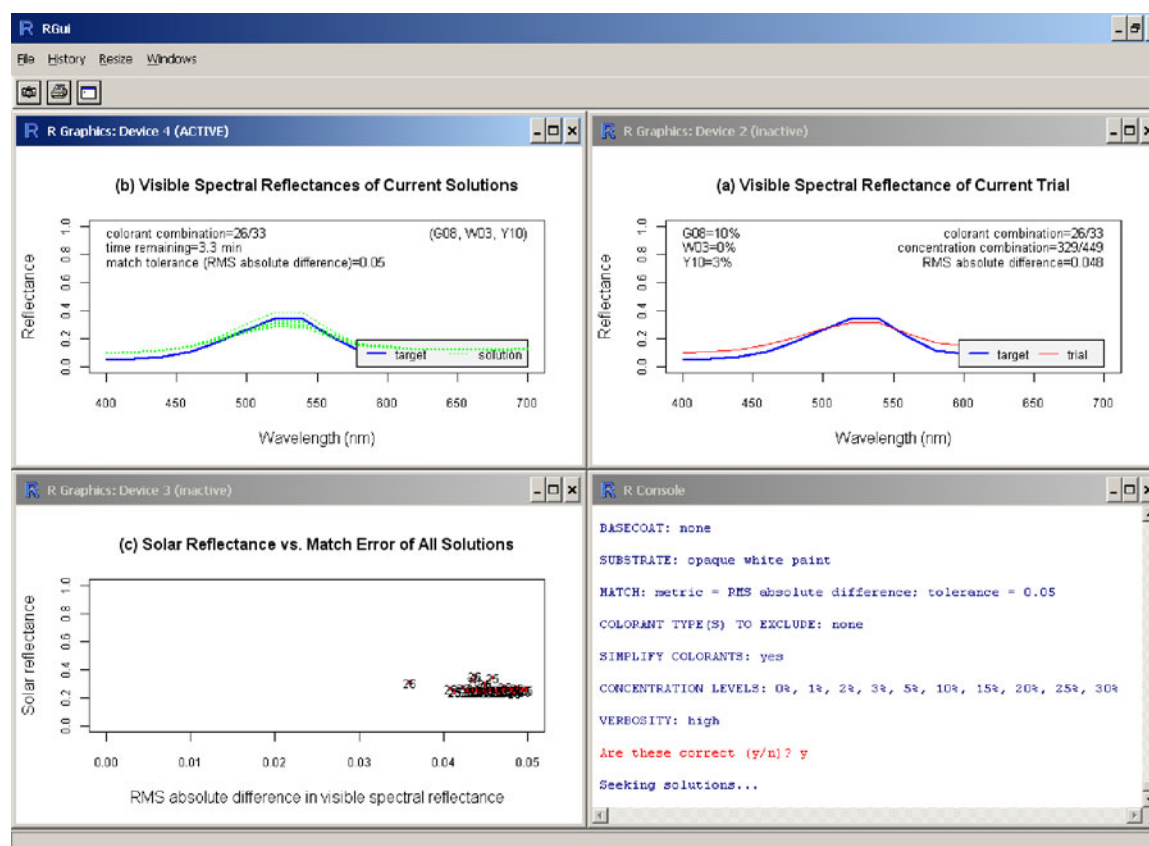


Figure 3. Pinwheel™ screen shot.

Figure 4 shows one of 163 acceptable solutions found by Pinwheel™. Solutions are ordered by descending solar reflectance, so solution 2 (shown here) is that with the second highest solar reflectance. It achieves a solar reflectance of 0.38 using volume concentrations of 1% phthalocyanine green and 1% iron oxide yellow in an otherwise clear 25- μm coating over an opaque white substrate.

Pinwheel™ is currently being tested by five manufacturers. Its user's manual can be found in Attachment 2.

Solution 2/163

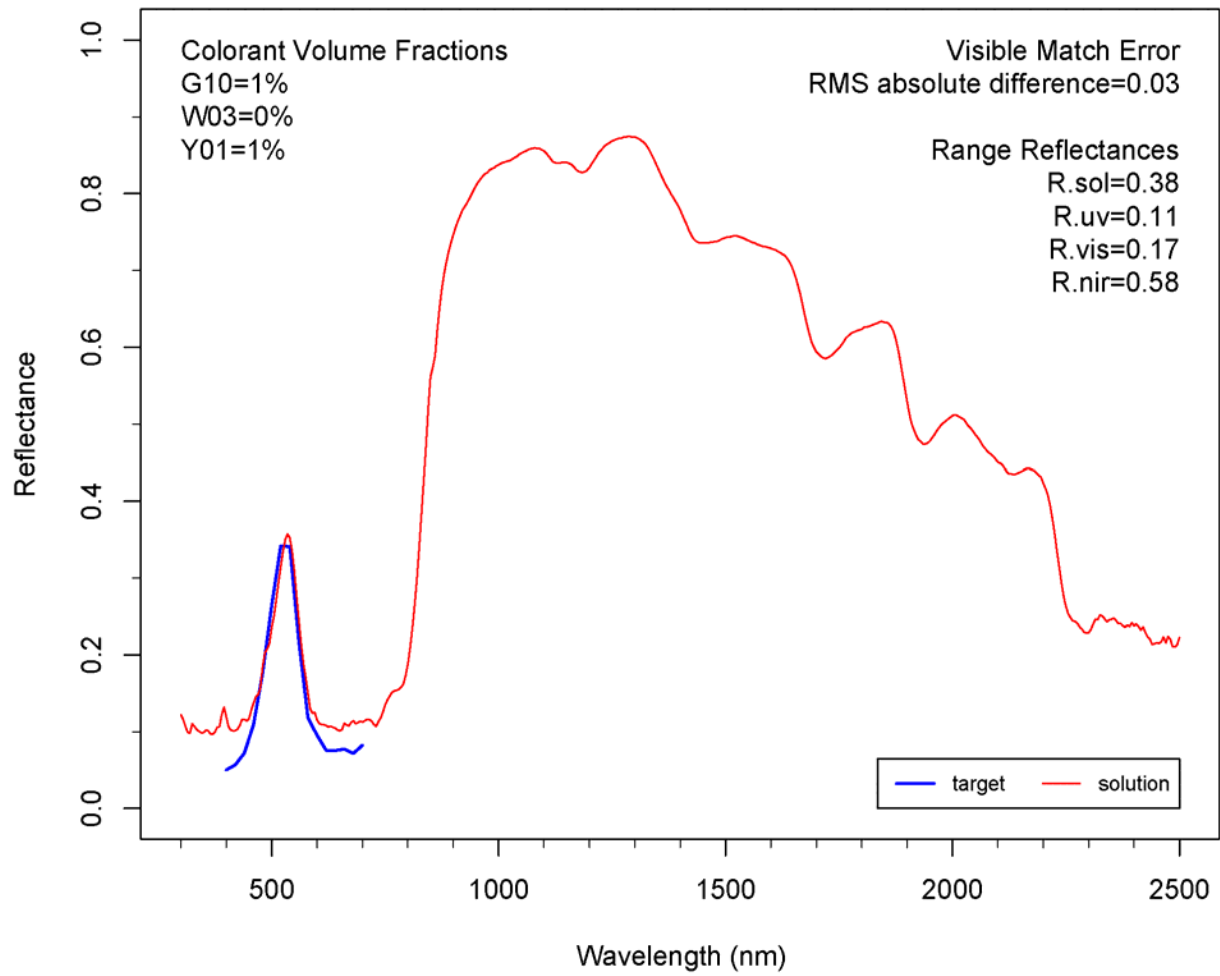


Figure 4. Solar spectral reflectance of a Pinwheel™-formulated cool coating (“solution”) designed to match the visible spectral reflectance of a particular shade of green (“target”).

Task 2.4.3: Develop a Database of Cool-Colored Pigments

To help the roofing industry identify cool pigments to use and hot pigments to avoid in their coatings, the LBNL researchers have produced a browsable HTML database detailing the solar spectral optical properties of 87 single-colorant (“masstone”) pigmented coatings. It also includes the solar spectral optical properties of 104 tints (mixtures of single colors with white) and 32 binary mixtures of nonwhite colors. The database charts the solar spectral reflectance, transmittance, absorptance, backscattering coefficient, and absorption coefficient of each pigmented coating, and also presents images, commentary, and a chemical description of each pigment (Figure 5). Machine-readable datafiles are also included.

Figure 6 shows the first index page of the online database, including links to detail pages for four white pigments and 21 black/brown pigments. A typical detail page includes links to a datasheet from the pigment’s manufacturer; commentary about the pigment from the LBNL articles produced for Task 2.4.1; large images of the pigment’s masstone, tint, and binary nonwhite mixture films; and charts and tables of the solar spectral properties of these films (Figure 5). The tabular information available for each pigment is detailed in Table 4. The database is online at <http://Coolcolors.LBL.gov>.

The database summary can be found in Attachment 3.

[R03] Red Iron Oxide (iii)

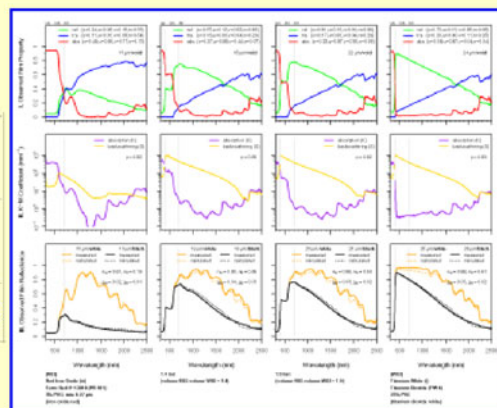
Paint Code	R03
Paint Name	Red Iron Oxide (iii)
Pigment Name	Ferro Red V-13810 (PR 101)
Color Family	Red/Orange
Color Subfamily	iron oxide red
Mean Particle Size (microns)	0.27
Dry Film PVC	3%
Pigment Datasheet	available
Paint Datasheet	unavailable
LBNL Commentary	available

Masstone and Mixtures with White (Tints)

[R03] Red Iron Oxide (iii) +
[W03] Titanium White (i)

image over white				
image over black				
spectral datafile	R03 masstone	R03 tint 1:4	R03 tint 1:9	W03 masstone

[guide to reading spectral datafiles](#)



Mixtures with Nonwhite Colors

[R03] Red Iron Oxide (iii) +
[B16] Iron Titanium Brown Spinel (i)

image over white			
image over black			
spectral datafile	R03 masstone	R03+B16 mixture 1:1	B16 masstone

[guide to reading spectral datafiles](#)

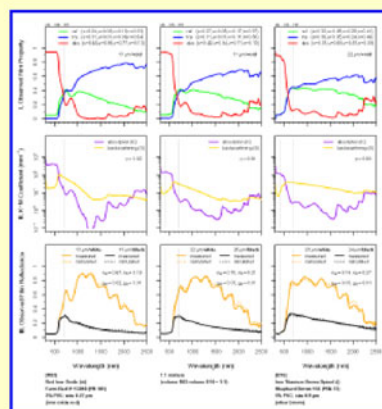




Figure 5. Description of an iron oxide red pigment in the Lawrence Berkeley National Lab pigment database



BERKELEY LAB

A product of the [Cool Colored Roofing Materials Project](#), a [California Energy Commission](#) sponsored collaboration between [Lawrence Berkeley National Laboratory](#), [Oak Ridge National Laboratory](#), and their 16 industrial partners: [3M Industrial Minerals](#), [Akzo-Nobel](#), [American Rooftile Coatings](#), [BASF Industrial Coatings](#), [CertainTeed](#), [Custom-Bilt Metals](#), [Eik Corporation](#), [Ferro Corporation](#), [GAF Materials Corporation](#), [Hanson Roof Tile](#), [ISP Minerals Incorporated](#), [MCA Tile](#), [MonierLifeTile LLC](#), [Owens Corning](#), [Shepherd Color Company](#), and [Steelscape Incorporated](#).



PIER

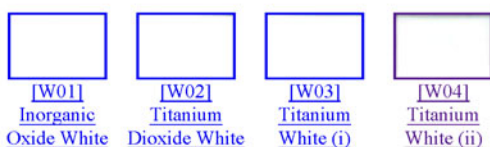
Public Interest Energy Research

Lawrence Berkeley National Laboratory Pigment Database

characterizing the solar spectral radiative properties
of conventional and cool pigmented coatings

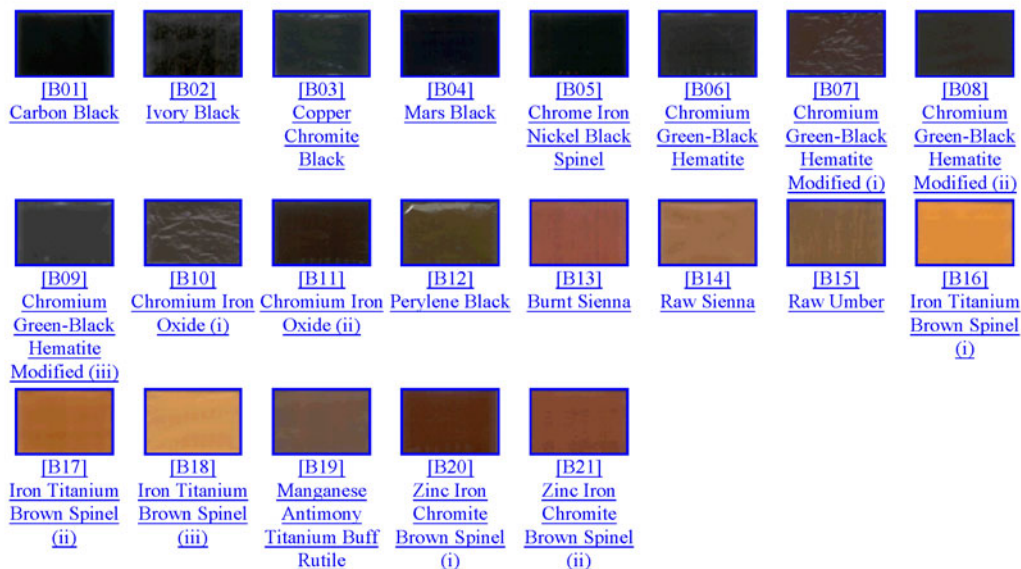
Ronnen Levinson, Paul Berdahl, and Hashem Akbari
Heat Island Group
Lawrence Berkeley National Laboratory
Berkeley, CA
<http://CoolColors.LBL.gov>

White



source: Lawrence Berkeley National Lab

Black/Brown



source: Lawrence Berkeley National Lab

Figure 6. First index page of the LBNL Pigment database, including links to the detail pages of 4 white pigment and 21 black/brown pigments. The remaining index pages link to the detail pages of 62 more pigments.

instructions	how to view and interpret this datafile
comments	authorship and disclaimer
computation date	when K-M coefficients were calculated
color family	white, black/brown, blue/purple, green, red/orange, yellow, or pearlescent
pigment category	pigment chemistry or characteristic (e.g., cobalt titanate green or non-selective black)
code	used to identify this pigment in our pigment characterization paper (note: this value likely to be replaced)
paint name	assigned by the paint manufacturer
pigment name	assigned by the pigment manufacturer
internal description	LBNL's description of masstone, tint, or mixture
component names	LBNL's description of the paint's components
component ratios	parts by volume of each component
dry-film PVC	pigment volume concentration (volume pigment:volume paint) in dry film
delta.v (microns)	thickness of film sample over void background [exclusive of substrate, if present] (μm)
delta.w (microns)	thickness of film sample over opaque white background [exclusive of background and substrate, if present] (μm)
delta.b (microns)	thickness of film sample over opaque black background [exclusive of background and substrate, if present] (μm)
sigma	non-spectral forward scattering ratio
spectral ranges	definitions of solar, ultraviolet, visible, and near-infrared ranges used in spectral averaging
R.tilde.fv averages	spectrally averaged, irradiance-weighted values of the measured reflectance of the film over a void background
T.tilde.fv averages	spectrally averaged, irradiance-weighted values of the measured transmittance of the film over a void background
A.tilde.fv averages	spectrally averaged, irradiance-weighted values of the measured absorptance of the film over a void background
R.tilde.fw averages	spectrally averaged, irradiance-weighted values of the measured reflectance of the film over an opaque white background
R.tilde.fb averages	spectrally averaged, irradiance-weighted values of the measured reflectance of the film over an opaque black background
R.tilde.ow averages	spectrally averaged, irradiance-weighted values of the measured reflectance of the opaque white background
lambda (nm)	wavelengths at which spectral values are presented
insolation ($\text{W}/\text{m}^2/\text{nm}$)	air-mass 1.5 hemispherical solar spectral irradiance ($\text{W m}^{-2} \text{ nm}^{-1}$)
R.tilde.fv	measured spectral reflectance of the film over a void background
T.tilde.fv	measured spectral transmittance of the film over a void background
A.tilde.fv	measured spectral absorptance of the film over a void background
R.tilde.fw	measured spectral reflectance of the film over an opaque white background
R.tilde.fb	measured spectral reflectance of the film over an opaque black background
K (1/mm)	Kubelka-Munk (K-M) spectral absorption coefficient (mm^{-1})
S (1/mm)	K-M spectral backscattering coefficient (mm^{-1})
R.inf	continuous refractive index (CRI) spectral reflectance of an opaquely thick film
R.tilde.inf	observed spectral reflectance of an opaquely thick film
R.tilde.fw.calc	observed spectral reflectance of the film over an opaque white background, as computed from the K-M coefficients
R.tilde.fb.calc	observed spectral reflectance of the film over an opaque black background, as computed from the K-M coefficients
T.v	internal transmittance of the film
q.i.at.zero	diffuse fraction q of the downflux i exiting the bottom of the film ($z = 0$)
q.j.at.delta	diffuse fraction q of the upflux j exiting the top of the film ($z = \delta$)
omega.i.at.zero	interface reflectance ω to the downflux i exiting the bottom of the film ($z = 0$)
omega.j.at.delta	interface reflectance ω to the upflux j exiting the top of the film ($z = \delta$)

Table 4. Pigment properties tabulated in the LBNL pigment database.

Task 2.5: Development of Prototype Cool-Colored Roofing Materials

We estimate that roofing shingles, tiles, and metal panels comprise more than 80% (by roof area) of the residential roofing market in the western United States. In this project, we have collaborated with manufacturers of many roofing materials in order to evaluate the best ways to increase the solar reflectance of these products. The results of our research have been utilized by the manufacturers to produce cool roofing materials. To date and as the direct result of this collaborative effort, manufactures of roofing materials have introduced cool shingles and cool concrete tile coatings, and cool concrete tiles; and significantly expanded the production of cool clay tiles and cool metal roofs.

Task 2.5.1: Review of Roofing Materials Manufacturing Methods

The objective of this subtask was to compile information on roofing materials manufacturing methods. We contacted several representative manufacturers of various roofing materials to obtain information on the processes used to color their products. Also, we reviewed literature on the fabrication and coloration of roofing materials.

Our analysis has suggested that cool-colored roofing materials can be manufactured using the existing equipment in production and manufacturing plants. The three principle ways to improve the solar reflectance of roofing materials including: (1) using of raw materials with high solar reflectance, (2) using cool pigments in the coating; and (3) applying a two-layered coloring technique using pigmented materials with high solar reflectance as an under-layer. Although all these options are in principle easy to implement, they may require changes to current production techniques that may add to cost and market competitiveness of the finished products.

Application of cool-colored pigments in metal roofing materials may require the least change to the existing production processes. As in the cases of tile and fiberglass shingle, cool pigments can be applied to metal via a single or a double-layered technique. If the raw metal is highly reflective, a single-layered technique may suffice.

Additional quality control measurements may be required to verify that coatings are truly NIR-reflective.

The results of this study were published as a two-part article in *Western Roofing* magazine. A copy of the final report for this study is enclosed in Attachment 4.

Task 2.5.2: Design Innovative Methods for Application of Cool Coatings to Roofing Materials

In addition to using NIR reflective pigments in the manufacture of cool roofing materials, application of novel engineering techniques can further economically enhance the solar reflectance of colored roofing materials. Cool-colored pigmented coatings are partly transparent to NIR light; thus, any NIR light not reflected by the cool pigmented coating is transmitted to its substrate, where it can be absorbed. A reflective basecoat can be used to increase the system's NIR and solar reflectance. This method is referred as a "two-layered," or "bilayer," technique.

We have detailed our innovative engineering methods in an article in press in the academic journal *Solar Energy Materials & Solar Cells*. A prepress draft of this article is included in Attachment 5.

Figure 7 demonstrates the application of the two-layered technique to manufacture cool colored materials. A thin layer of dioxazine purple (14–27 μm) is applied on four substrates: (a) aluminum foil ($\sim 25 \mu\text{m}$), (b) opaque white paint ($\sim 1000 \mu\text{m}$), (c) non-opaque white paint ($\sim 25 \mu\text{m}$), and (d) opaque black paint ($\sim 25 \mu\text{m}$). As it can be seen (and is confirmed by visible reflectance spectrum), the color of the material is black. However, the solar reflectance of the sample exceeds 0.40 when applied to an opaque white or aluminum foil substrate; while its solar reflectance over a black substrate is only 0.05.

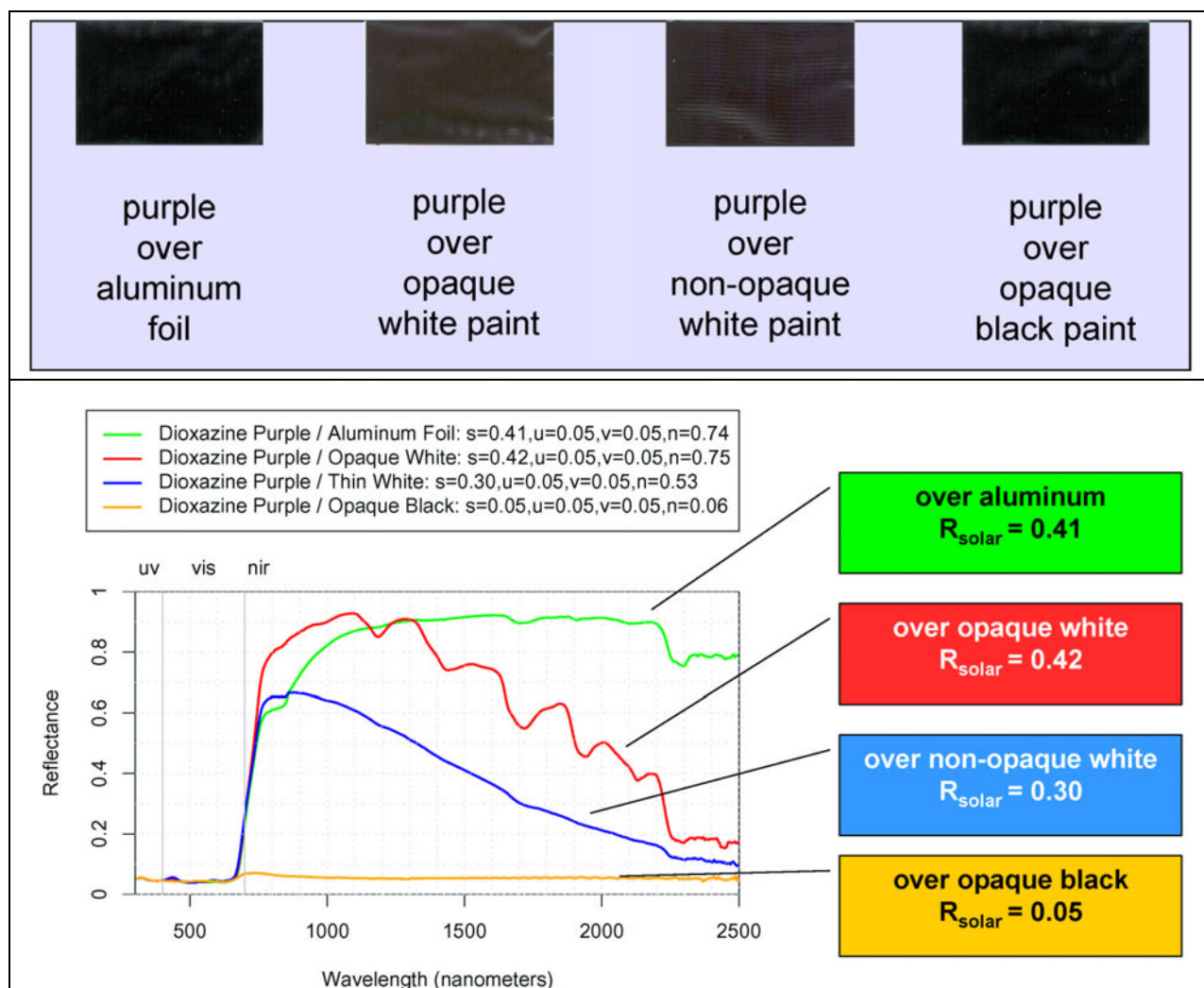


Figure 7. Application of the two-layered technique to manufacture cool colored materials

Shingles

The solar reflectance of a new shingle, by design, is dominated by the solar reflectance of its granules, which cover over 97% of its surface. Until recently, the way to produce granules with high solar reflectance has been to use a coating pigmented with titanium dioxide (TiO_2) rutile white. Because a thin TiO_2 -pigmented coating is reflective but not opaque in the NIR, multiple layers are needed to obtain high solar reflectance. This technique has been used to produce

“super-white” (meaning truly white, rather than gray) granulated shingles with solar reflectances exceeding 0.5 (see Figure 8).

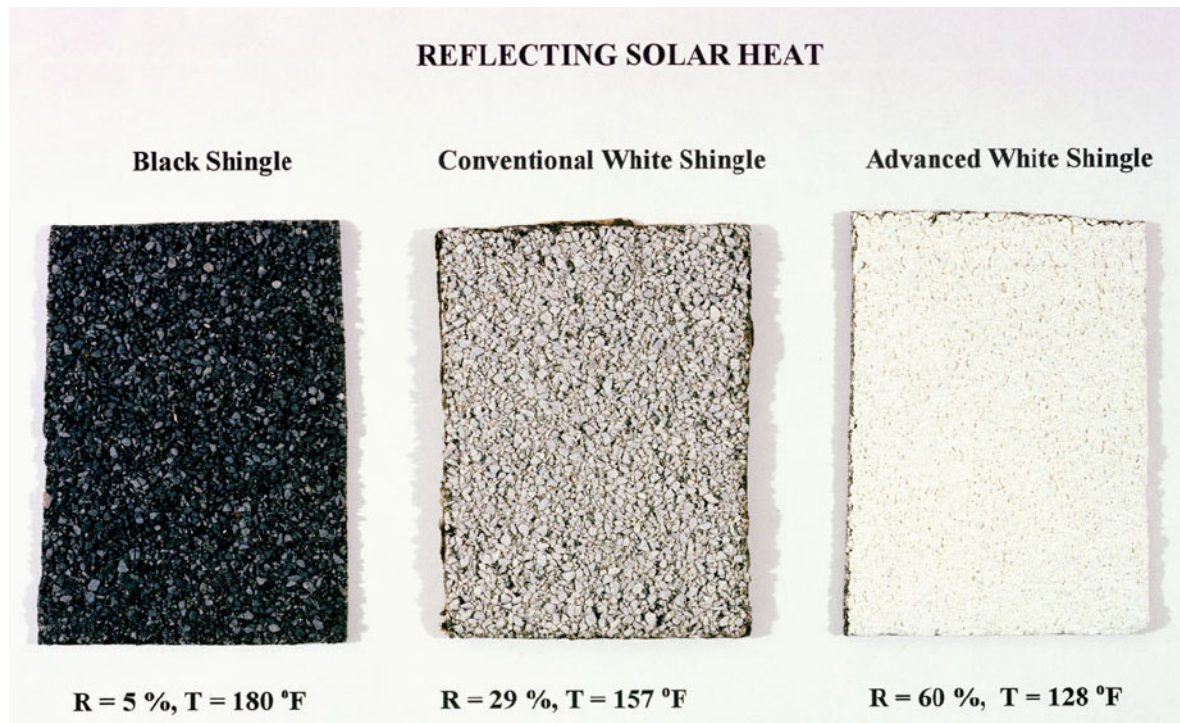


Figure 8. Development of super white shingles

Although white roofing materials are popular in some areas (e.g., Greece, Bermuda; see Figure 9), many consumers prefer aesthetically pleasing non-white roofs. Manufacturers have also tried to produce colored granules with high solar reflectance by using nonwhite pigments with high NIR reflectance. To increase the solar reflectance of colored granules with cool pigments, multiple color layers, a reflective undercoating, and/or reflective aggregate should be used. Obviously, each additional coating increases the cost of production.



Bermuda



Santorini (Greece)

Figure 9. White roofs and walls are used in Bermuda and Santorini (Greece)

In close collaboration with our partners at ISP Minerals, 3M Mineral, Elk, GAF, and CertainTeed, the labs have developed over 100 single and multiple-color shingle prototypes. Figure 10 illustrates the iterative development of a cool black shingle prototype by industrial partner ISP Minerals. A conventional black roof shingle has a reflectance of about 0.04. Replacing the granule's standard black pigment with a cool NIR-scattering black pigment (prototype 1) increases the solar reflectance of the shingle to 0.12. Incorporating a thin white sublayer (prototype 2) raises the shingle's solar reflectance to 0.16; using a thicker white sublayer (prototype 3) increases the shingle's solar reflectance to 0.18. The figure also shows an approximate performance limit (solar reflectance 0.25) obtained by applying 25-micron NIR-reflective black topcoat over an opaque white background.

Several cool shingles have been developed within the last year. Figure 11 shows examples of prototype cool shingles and compares the solar reflectance of each with their conventional pigmented counterpart of the same color.

In parallel to the above efforts, two of our partners (3M and Elk) have developed cool-colored shingles for three popular colored products. On March 2005, Elk formally announced the availability of the three cool colored shingles. We are currently testing the performance of these cool shingles in two demonstration houses in Redding, CA. Figure 12 shows two houses with cool colored roofing shingles from Elk.

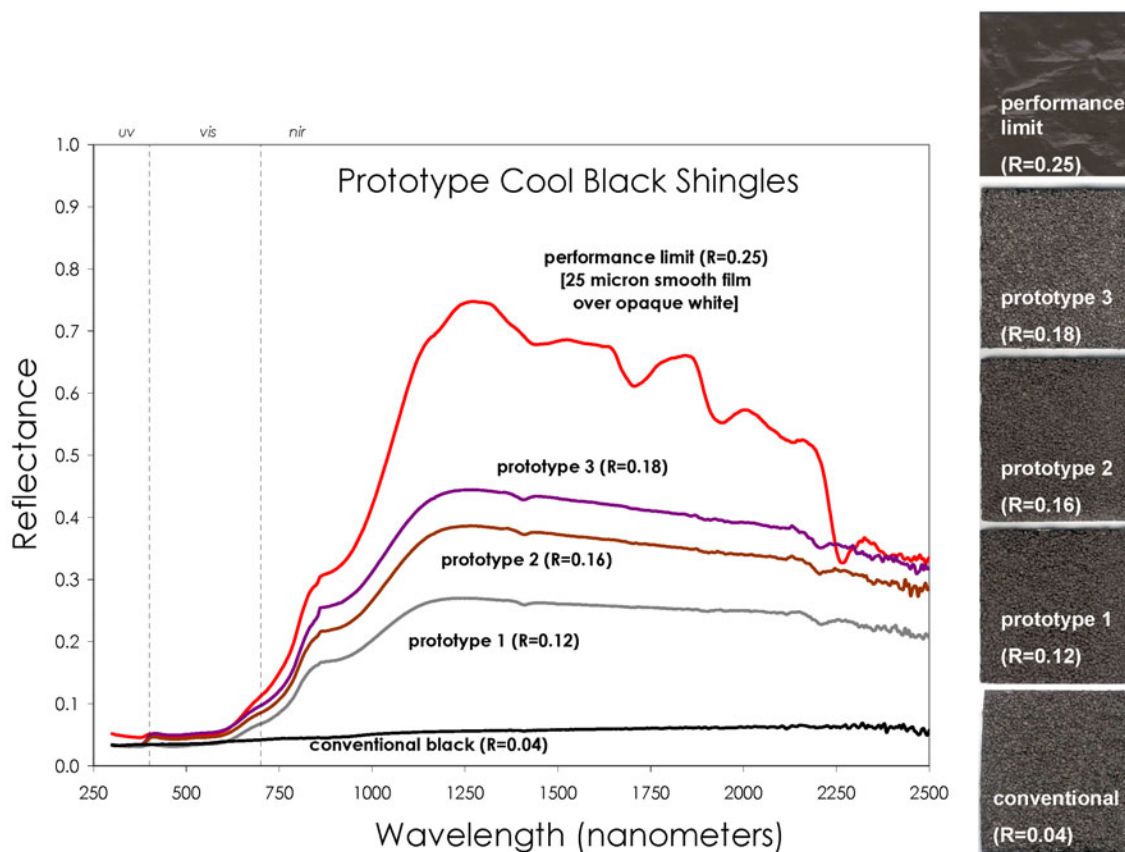
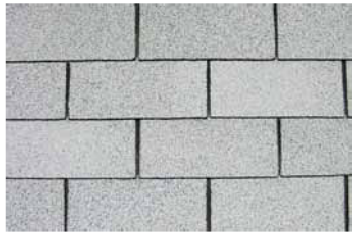


Figure 10. Development of a cool black shingle by industrial partner ISP Minerals. Shown are the solar spectral reflectances, images, and solar reflectances (R) of a conventional black shingle, three prototype cool black shingles, and smooth cool black film over an opaque white background.

Standard Shingles



R=0.23



R=0.27

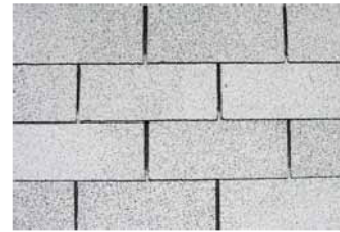


R=0.28

Cool Shingles



R=0.28



R=0.36



R=0.37

Figure 11. Examples of prototype cool shingles.



Figure 12. Application of cool colored roofing shingles on two houses advertised by Elk Corp.

Tiles and Tile Coatings

Clay and concrete tiles are used in many areas around the world. In the U.S., clay and concrete tiles are more popular in the hot climate regions. There are three ways to improve the solar reflectance of colored tiles: (1) use clay or concrete with low concentrations of light-absorbing impurities, such as iron oxides and elemental carbon; (2) color the tile with cool pigments contained in a surface coating or mixed integrally; and/or (3) include an NIR-reflective (e.g., white) basecoat beneath an NIR-transmitting colored topcoat. Although all these options are in principle easy to implement, they may require changes in the current production techniques that may add to cost of the finished products. Colorants can be included throughout the body of the tile, or used in a surface coating. Both methods need to be addressed.

Consortium member American Rooftile Coatings has developed a palette of cool nonwhite coatings for concrete tiles. Each of the COOL TILE IR COATINGS™ shown in Figure 13 has a solar reflectance better than 0.40. The solar reflectance of each cool coating exceeds that of a color-matched, conventionally pigmented coating by 0.15 (terracotta) to 0.37 (black).

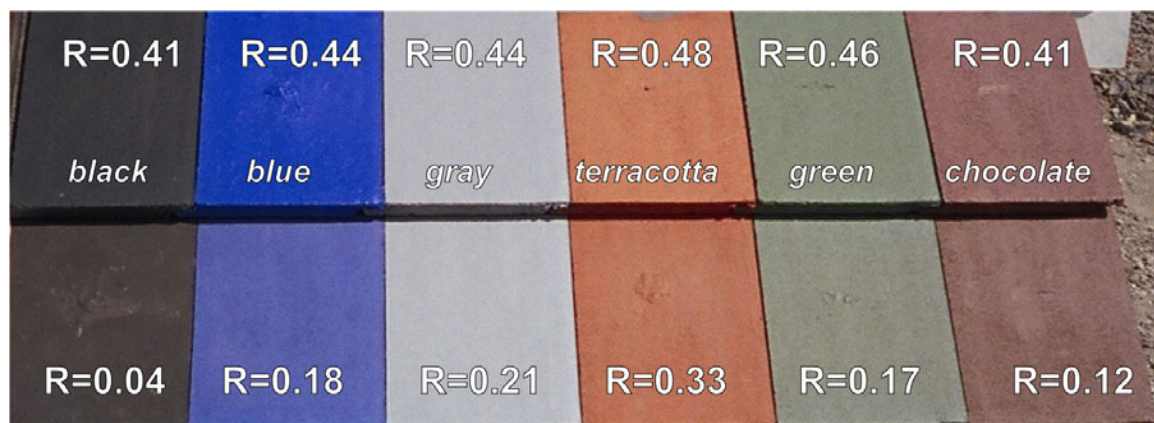


Figure 13. Palette of color-matched cool (top row) and conventional (bottom row) roof tile coatings developed by industrial partner American Rooftile Coatings. Shown on each coated tile is its solar reflectance R

MCA tiles is producing several cool nonwhite clay tile products (see Table 5), and MonierLifetile has developed several cool nonwhite concrete tile prototypes. We are currently testing a cool-colored concrete tile on a demonstration house in Sacramento and a cool-colored clay tile on the attic test assembly at ORNL.









Model	Color	Initial solar reflectance	Solar reflectance after 3 years
Weathered Green Blend		0.43	0.49
Natural Red		0.43	0.38
Brick Red		0.42	0.40
White Buff		0.68	0.56
Tobacco		0.43	0.41
Peach Buff		0.61	0.48
Regency Blue		0.38	0.34
Light Cactus Green		0.51	0.52

Table 5. Sample cool colored clay tiles and their solar reflectances (Source: <http://www.MCA-Tile.com>)

Metal Panels

Metal roofing materials are installed on a small (but growing) fraction of the U.S. residential roofs. Historically metal roofs have had only about 3% of the residential market. However, the architectural appeal, flexibility, and durability, due in part to the cool-colored pigments, has steadily increased the sales of painted metal roofing, and as of 2002 its sales volume has increased to 8% of the residential market, making it the fastest growing residential roofing product (F.W. Dodge 2002). Metal roofs are available in many colors and can simulate the shape and form of many other roofing materials (see Figure 14). Application of cool-colored pigments in metal roofing materials may require the fewest number of changes to the existing production processes. As in the cases of tile and asphalt shingle, cool pigments can be applied to metal via a single or two-layered technique. If the metal substrate is highly reflective, a single-layered technique may suffice. The coatings for metal shingles are thin, durable polymer materials. These thin layers use materials efficiently, but limit the maximum amount of pigment present. However, the metal substrate can provide some NIR reflectance if the coating is transparent in the NIR. Several manufactures have developed cool colored metal roof products.

Cool nonwhite coatings have been enthusiastically adopted by premium coil coaters and metal roofing manufacturers. BASF Industrial Coatings has launched “Superl SP II™ ULTRA-Cool®,” a line of cool colored silicone modified polyester coatings that will eventually replace its conventional silicone modified polyester coatings. Coil-coater Steelscape, Inc. has recently introduced Spectrascape MBM, a cool Kynar coating for the metal building industry. A third industrial partner, CustomBilt, has switched over 250 of its metal roofing products to cool colors. We are currently testing a cool-colored metal roof on a demonstration house in Sacramento.



(a)



(b)



(c)



(d)



(e)



(f)



(g)



(h)



(i)



(j)



(k)



(l)

Figure 14. Simulated roofing products made from metal: (a) Advanta Shingles; (b) Bermuda Shakes; (c) Castle Top; (d) Dutch Seam Panel; (e) Granutiles; (f) Perma Shakes; (g) Scan Roof Tile; (h) Snap Seam Tile; (i) Techo Tile; (j) Verona Tile; (k) Oxford Shingles; and (l) Timbercreek Shakes. Products a-j are manufactured by ATAS International, Inc., while products k and l are manufactured by Classic Products, Inc. (Photos courtesy of ATAS International and Classic Products)

Task 2.5.3: Accelerated Weathering Testing (Durability of Cool Nonwhite Coatings)

Roofing materials fail mainly because of three processes: (1) gradual changes to physical and chemical composition induced by the absorption of ultraviolet (UV) light; (2) aging and weathering (e.g., loss of plasticizers in polymers and low-molecular-weight components in asphalt), which may accelerate as temperature increases; and (3) diurnal thermal cycling, which stresses the material by expansion and contraction. Our goal is to clarify the material degradation effects due to UV absorption and heating. Durability performance must be demonstrated for homebuilders to adopt cool-pigmented tile and asphalt shingle roof products.

Shepherd Color Company and 3M Minerals provided time in their weatherometers for evaluating the effect of fluorescent (UV) light exposure and xenon-arc exposure on the solar reflectance, the fading and gloss retention of clay, concrete, painted metal and asphalt shingle roof products. Clay tiles were provided by Maruhachi Ceramics of America. Painted PVDF metal samples with and without cool pigmented colors were provided by BASF and Steelscape. Shingles were provided by U.S. companies preferring their products' identity remain confidential; however, the data for shingles with and without cool pigments are provided in coded format. Detail of the accelerated and natural sunlight test results are provided in the Task 2.5.3 report, Attachment 6.

Results of accelerated fluorescent (UV) light exposures show that pigment stability and discoloration resistance of the painted metals, concrete tiles and clay tiles with cool pigments are as good as those commercially available. Independent UV testing by BASF produced similar findings. The fade resistance of painted metal cool colored blue and yellow masstones is much improved over the respective standard colors. Blue, especially a blue tint, is well known to fade; however, the cool colored masstone blue shows excellent fade resistance. The retention of gloss from the original color was also verified for the cool pigments as compared to standard production pigments. A higher gloss paint is often preferred because it provides a homeowner greater wear and therefore reduced maintenance costs.

Results for asphalt shingles were just as promising and showed no deleterious effects on solar reflectance or total color change after being subjected to 5000 hours of fluorescent or xenon-arc exposures (see Figure 15). Cool-pigmented shingles coded A and E had a total color change (ΔE) less than 1.5 after 5000 hours of UV exposure. In contrast, their conventionally pigmented counterparts had ΔE 's that were 50% higher for Code A and 100% higher for Code E. The ΔE for the Code C shingle with cool-pigments exceeded 2.0 after 1000 hours then it dropped below 1.0 after 5000 hours. Reasons for the behavior are unknown; however, overall the data clearly shows that the cool-pigmented shingles when subjected to direct solar UV radiation (UVB-340 lamp simulating direct solar UV radiation) perform just as well as standard products accepted on the open market. The asphalt shingles with cool pigments do not lose solar reflectance, and they remain fade resistant.

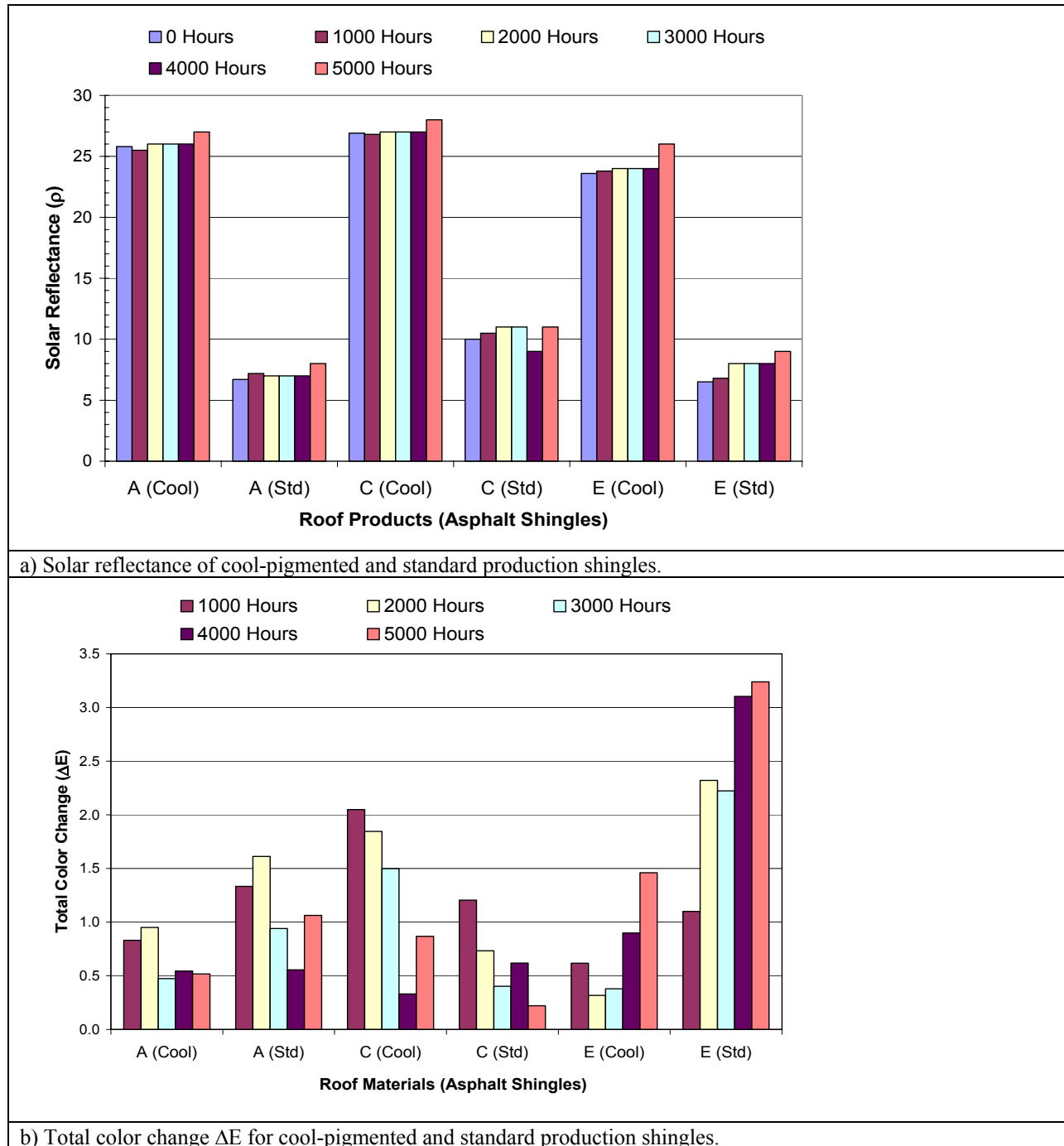


Figure 15. (a) Solar reflectance (b) and total color change of asphalt shingles exposed to accelerated direct UV radiation simulating solar's short-wave irradiance (data courtesy of Shepherd Color Company)

Task 2.6: Field-Testing and Product Useful Life Testing

Task 2.6.1: Building Energy-Use Measurements at California Demonstration Sites

We have set up a residential demonstration site in Fair Oaks, CA (near Sacramento) consisting of two pairs of single-family, detached houses roofed with painted metal shakes and concrete tile. We have also set up two houses in Redding, CA to demonstrate asphalt shingles. The demonstration pairs each include one building roofed with a cool-pigmented product and a second building roofed with a conventionally (warmer) pigmented product of nearly the same color. The paired homes are adjacent, and share the same floor plan, roof orientation, level of blown ceiling insulation of $3.4 \text{ m}^2\text{K/W}$ (R-19 insulation), and all have air-handlers and air-delivery duct work in the attic. Demonstration homes in Fair Oaks have soffit and gable vents, while the homes in Redding are equipped with soffit and ridge vents. The homes will be monitored through at least summer 2006.

Temperatures at the roof surface, on the underside of the roof deck, in the mid-attic air, at the top of the insulation, on the interior ceiling's sheet rock surface, and inside the building are logged continuously by a data acquisition system. Relative humidity in the attic air and the residence are also measured. Heat flux transducers are embedded in the sloped roofs and the attic floor to measure the roof heat flows and the building heat leakage. We have instrumented the building to measure the total house and air-conditioning power demands. A fully instrumented meteorological weather station is set up to collect the ambient dry bulb temperature, the relative humidity, the solar irradiance, and the wind speed and wind direction.

One of the Fair Oaks homes roofed with low-profile concrete tile was colored with a conventional chocolate brown coating (solar reflectance 0.10), while the other was colored with a matching cool chocolate brown with solar reflectance 0.41. The attic air temperature beneath the cool brown tile roof has been measured to be 3 to 5 K cooler than that below the conventional brown tile roof during a typical hot summer afternoon. The results for the two pair of homes roofed with painted metal shakes and with asphalt shingles are just as promising. There the attic air temperature beneath the cool brown metal shake roof (solar reflectance 0.31) was measured to be 5 to 7 K cooler than that below the conventional brown metal shake roof. Attic air temperature below the cool shingle (solar reflectance 0.26) was about 3 K cooler than the temperature below the conventional pigmented shingle roof.

The application of cool colored coatings reduced surface temperature of the cool pigmented roofs, which in turn reduced the average daytime heat flows through the roof deck by 20% for cool pigmented tile, by 32% for cool pigmented painted metal shakes and by 30% for cool pigmented asphalt shingle roofs as compared to each roof type's conventional counterpart.

The thermal data proved drops in the heat penetrating into the conditioned space which yields cooling and whole house electrical energy savings. Cool pigmented tile and cool pigmented metal shakes reduced the daytime whole house electrical energy by about 2 kWh per day.

As the temperature difference from the outdoor air to the home's interior air increases, the cooling savings also increase for the pair of shingle demonstrations (Figure 16). At an outdoor air-to-indoor air temperature difference of 10°C (about 32°C outdoor air temperature) the home with cool pigmented asphalt shingles uses about 6.3 kWh per day less electricity than the other

home with conventional shingles. This represents savings of about 0.90 kWh per day per ton of cooling capacity.

It is interesting to note that the hotter the outdoor air temperature the greater were the energy savings for the air-conditioners operating in all demonstration homes with cool pigmented roofs. The trend is small yet could be important in terms of Time Dependent Valuation of energy that places a premium cost on energy consumed during the hottest portion of the day.

The report for Task 2.6.1 documenting the thermal performance and electrical energy savings is provided in Attachment 7.

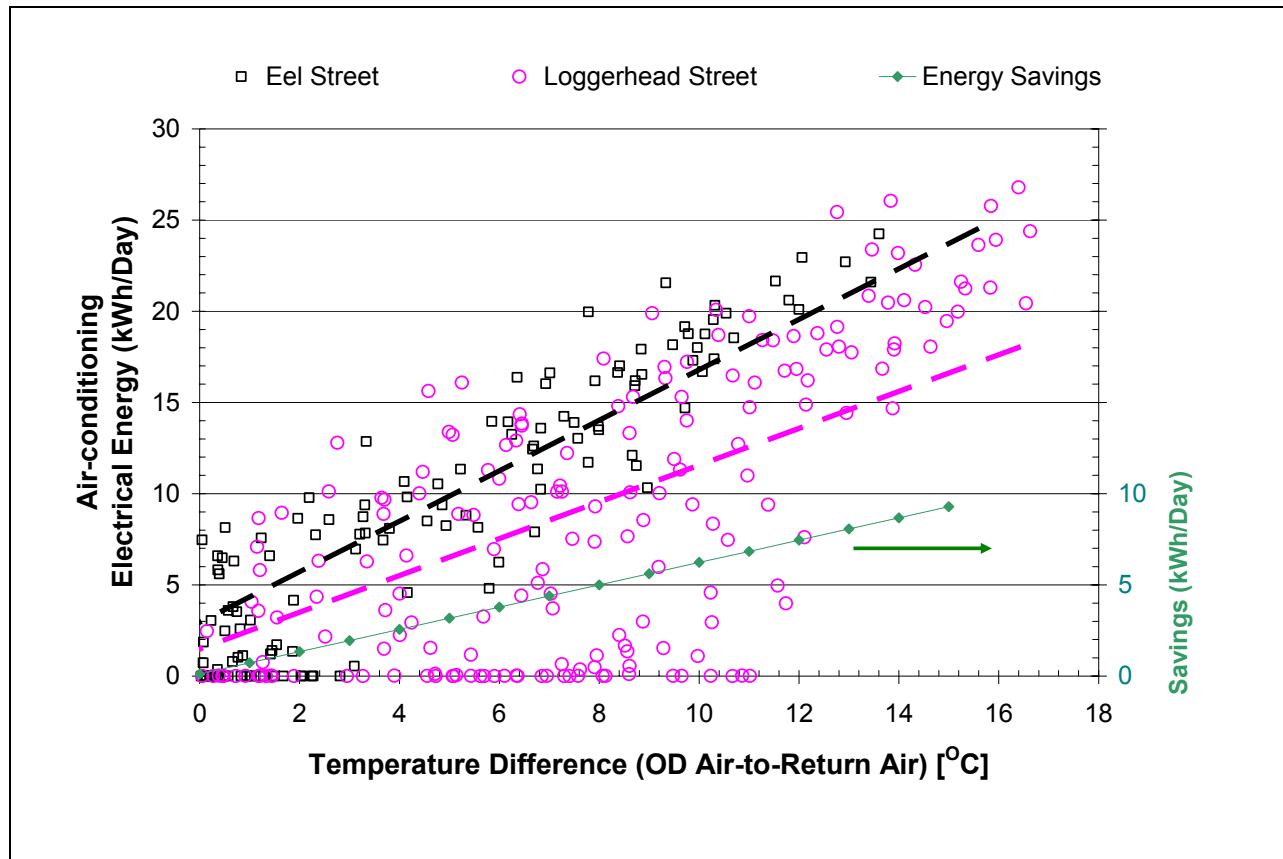


Figure 16. Daily air-conditioning energy consumption and savings, measured during the daylight hours from June through September 2005, for demonstrations with asphalt shingle roofs with and without cool pigments. The Redding demonstration homes each use two 3½ ton air-conditioners for comfort cooling.

Task 2.6.2: Materials Testing at Weathering Farms in California

In addition to accelerated testing reported in Task 2.5.3, we naturally weathered various types of conventionally- and cool-pigmented roofing products at seven CA sites. The final report is contained in Attachment 8 and has been submitted for journal review and publication for documenting the effect of soiling on the solar reflectance of the conventional- and cool-pigmented roof products.

Airborne particulate matter that settles on a roof can either reflect or absorb incoming solar radiation, dependent on the chemical content and size of the particles. These light scattering and absorption processes occur within a few microns of the surface, and can affect the solar reflectance of the roof. The long-term loss of reflectance appears driven by the ability of the particulate matter to cling to the roof and resist being washed off by wind and or rain.

Contaminants collected from samples of roof products exposed at the seven CA weathering sites were analyzed for elements including elemental and organic carbons and biomass to characterize the chemical profile of the particles soiling each roof sample and to identify those elements that degrade or enhance solar reflectance.

The chemical composition of particles deposited on the roof samples was very similar across the state of CA; there was no clear distinction from one region to another. Organic and elemental carbon (soot) was detected; however, the elemental carbon did not contribute significantly to the loss of solar reflectance. Dust particles (characterized by Ca and Fe) and organic carbon compensated for the loss of solar reflectance due to elemental carbon possibly because some particulate forms of these elements were light reflecting and contributed to the solar reflectance.

The loss in solar reflectance for painted metal and clay and concrete tile coupons was of the order 6% of the initial reflectance for this 2½ year time limited study (Figure 17). Solar reflectance of the cool pigmented coupons always exceeded that of the convention pigmented coupons. Climatic soiling did not cause the cool pigmented roof coupons to lose any more solar reflectance points than their conventional pigmented counterparts. The effect of roof slope appears to have more of an affect on lighter color roofs whose solar reflectance exceeds at least 0.5 and visually show the accumulation of airborne contaminants. However, precipitation and or wind sweeping helps restore most of the initial solar reflectance. The thermal emittance remained invariant with time and location and was therefore not affected by climatic soiling.

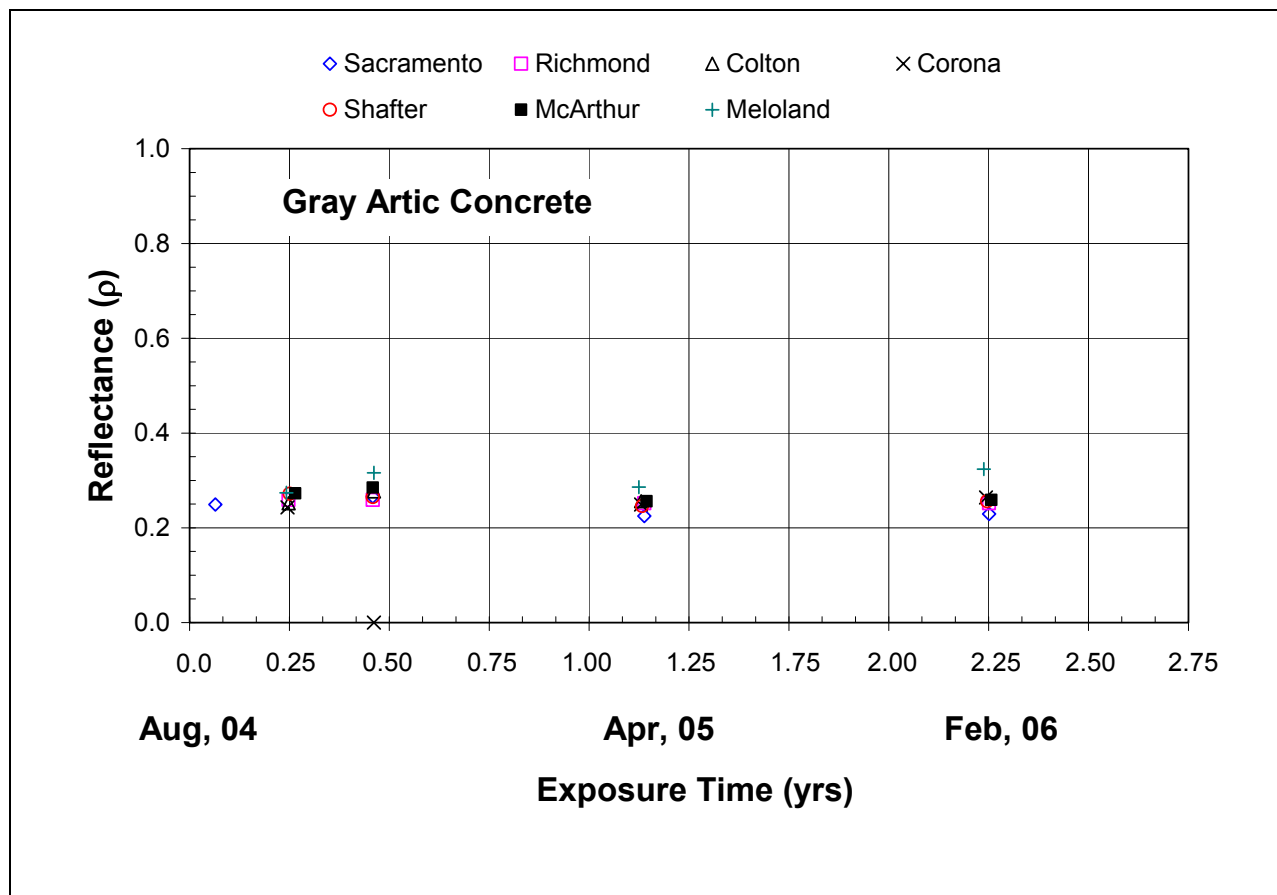


Figure 17. Solar reflectance of a concrete tile coupon (light gray color) exposed to climatic soiling at each of the seven CA weathering sites.

Task 2.6.3: Steep-slope Assembly Testing at ORNL

Cool color pigments and sub-tile venting of clay and concrete tile roofs significantly impact the heat flow crossing the roof deck of a steep-slope roof. Field measures for the tile roofs revealed a 70% drop in the peak heat flow crossing the deck as compared to a direct-nailed asphalt shingle roof. The Tile Roofing Institute (TRI) and its affiliate members are keenly interested in documenting the magnitude of the drop for obtaining solar reflectance credits with state and federal “cool roof” building efficiency standards. Tile roofs are direct-nailed or are attached to a deck with batten or batten and counter-batten construction. S-Mission clay and concrete tile roofs, a medium-profile concrete tile roof, and a flat slate tile roof were installed on fully instrumented attic test assemblies. Temperature measures of the roof, deck, attic, and ceiling, heat flows, solar reflectance, thermal emittance, and the ambient weather were recorded for each of the tile roofs and also on an adjacent attic cavity covered with a conventional pigmented and direct-nailed asphalt shingle roof. ORNL measured the tile’s underside temperature and the bulk air temperature and heat flows just underneath the tile for batten and counter-batten tile systems and compared the results to the conventional asphalt shingle.

Our measurements showed that the combination of improved solar reflectance afforded by cool pigmented colors and sub-tile venting reduced the noontime heat flow crossing the roof deck of the clay tile roof by 70% of the flow crossing the conventional shingle roof, which in turn, reduced the heat entering the conditioned space by 60% of the heat flow penetrating the ceiling of the attic assembly with shingle roof (solar reflectance of 0.093). The slate and medium-profile concrete roofs, having nearly the same surface properties as the conventional shingle, reduced the deck heat flow ~45% of that crossing the shingle roof because of sub-tile venting. Opening the ridge vent of the attics to allow both attic and sub-tile ventilation caused more heat to be exhausted out the ridge for both the S-Mission clay and the slate tile systems and therefore further improved the performance of the two tile roofs. The effect was more pronounced for the slate tile than observed for the S-Mission tile because the slate tile has less air leakage between tiles.

The heat transfer results imply that cool roof credits are obtainable for sub-tile venting. The effects of sub-tile venting and cool pigmented colors reduce the summertime heat penetrating into the conditioned space; however, in the winter the air gap adds an additional radiation heat transfer resistance thereby decoupling the conduction path for direct nailed roof products. Subsequently, the tile’s thermal mass and sub-tile venting have limited the wintertime heat loss to about the same loss observed for the direct nailed asphalt shingle in East Tennessee’s climate (Figure 18). Sub-tile venting therefore lessens the heating penalty associated with cool roof products. The improved summer performance coupled with the reduced heat losses during the winter as compared to a shingle roof show that offset-mounting roofs can provide the roof industry the opportunity to market cool pigmented roofs in climates that are predominated more by heating loads. Typically, the monetary breakeven point for cool roofs occurs where the ratio $(CDD/HDD)_{65}$ is about 0.4; however, sub-tile venting can move this climatic boundary of affordable energy cost savings farther north.

A report summarizing and analyzing the experimental data is enclosed in Attachment 9.

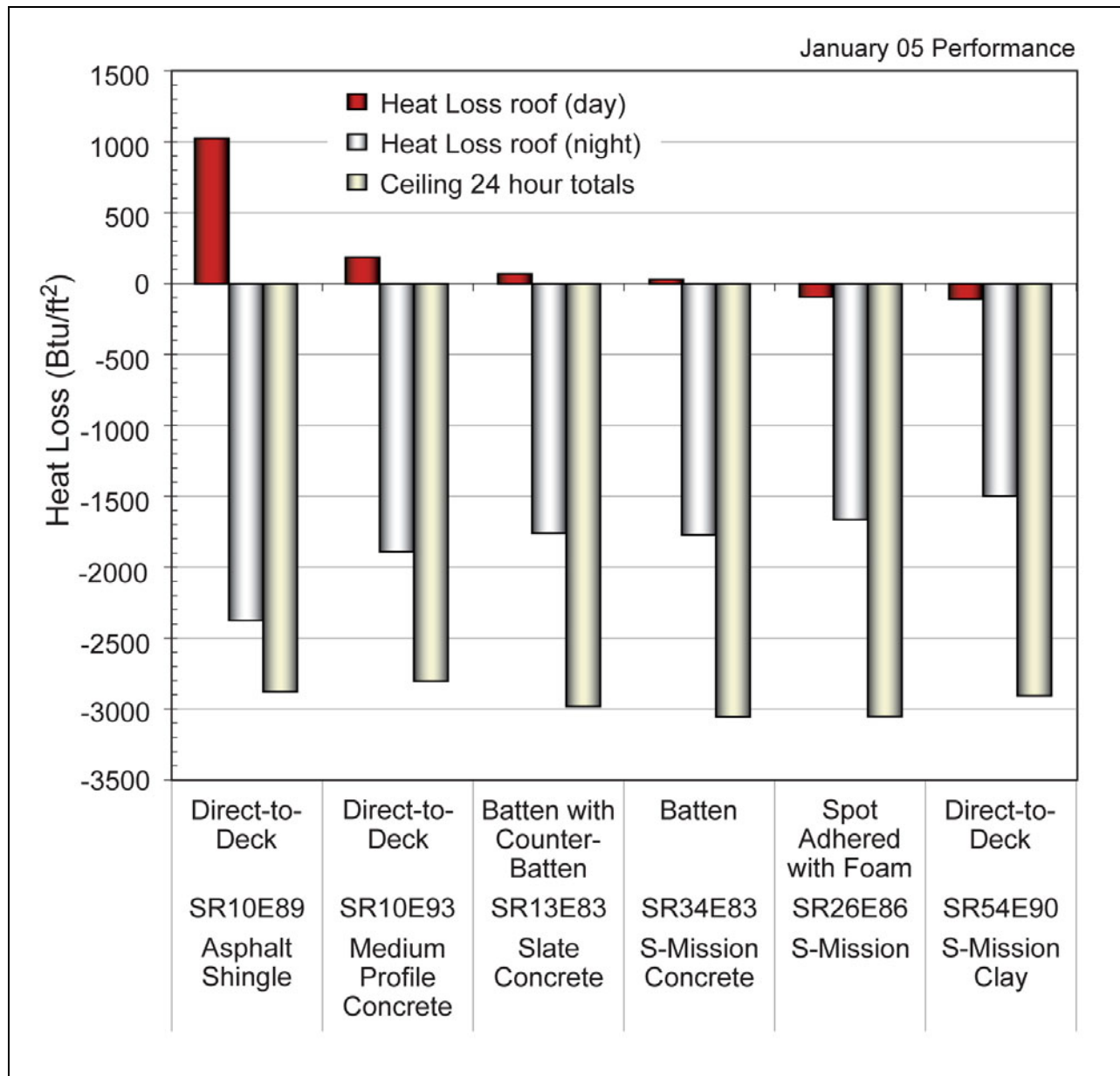


Figure 18. Integrated heat flow measured through the roof deck and the attic floor for all tile and shingle roofs field tested in East Tennessee during the month of January 2005. SR10E89 represents a solar reflectance of 0.10 and a thermal emittance of 0.89.

Task 2.6.4: Product Useful Life Testing

In this task we reviewed several aspects of the weathering of roofing materials. Degradation of materials initiated by ultraviolet radiation affects plastics used in roofing, as well as wood and asphalt. Elevated temperatures accelerate many deleterious chemical reactions and hasten diffusion of material components. Effects of moisture include decay of wood, acceleration of corrosion of metals, staining of clay, and freeze-thaw damage. Soiling of roofing materials causes objectionable stains and reduces the solar reflectance of reflective materials. (Soiling of non-reflective materials can also increase solar reflectance.) Soiling can be attributed to biological growth (e.g., cyanobacteria, fungi, algae), deposits of organic and mineral particles, and to the accumulation of fly ash, hydrocarbons and soot from combustion. We summarized the results of our work in a review article submitted to the journal *Construction and Building Materials*. A copy of the paper is enclosed in Attachment 10. Two specific examples illustrating weathering behavior are given below, taken from our paper.

Most of the ultraviolet-induced degradation mechanisms of polymeric roofing materials involve oxidation. That is, the absorption of an ultraviolet photon initiates material breakdown, but chemical combination with oxygen is also an essential step. Figure 19 shows how oxygen penetrates polypropylene during photo-oxidation, as evidenced by the carbonyl (C=O) group identified spectroscopically. We can see that after 1200 hours of exposure, oxygen has penetrated about 0.3 mm into this plastic. This oxygenated surface region becomes brittle and cracks (crazes). While this specific example utilizes polypropylene, similar behavior is seen in other organic building materials including asphalt, other plastics, and wood.

Ideally, roofing materials are engineered to be impervious to sunlight, moisture, and other elements of the weather. Thus, robust inorganic materials such as metal oxide pigments, minerals (such as the crushed stone for roofing granules), concrete, and clay are employed. Among organic materials, a few fluorinated polymers stand out as durable, and others such as asphalt can be used when an overlying ultraviolet-absorbing material provides UV protection. Wood is an example of an organic material that can even be used without a UV-absorbing overlayer. Wood does photo-oxidize, changes color, crazes, and is gradually eroded as it weathers. However, the rate of erosion of durable wood species, when kept dry, is very slow, so the lifetime is measured in decades. Figure 20 documents how the spectral reflectance of western red cedar roofing shingles changes as it ages. The color gradually becomes less red. It is interesting that the near-infrared reflectance of wood is larger than the visual (400 to 700 nm) reflectance; wood is naturally cool.

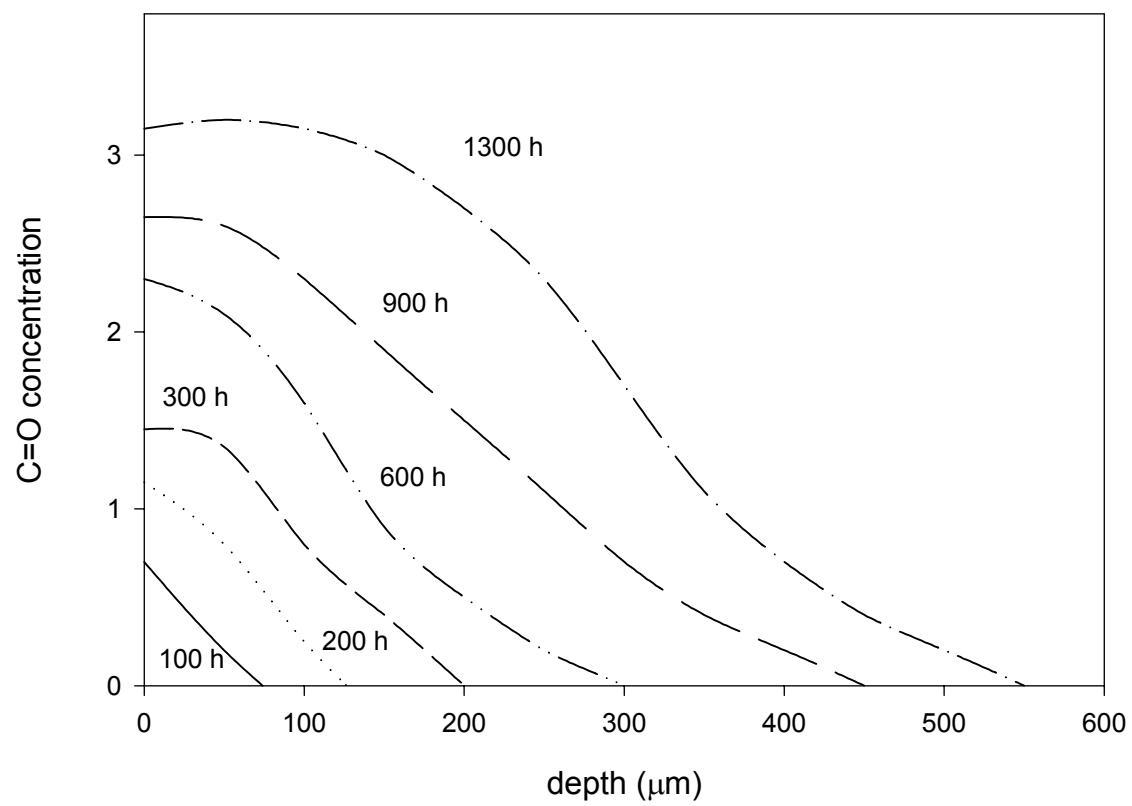


Figure 19. Oxidation (carbonyl) profiles measured during accelerated UV aging of polypropylene.

Spectral Reflectance of Western Red Cedar Roofing Shingles (fire retardant chemically pressure treated)

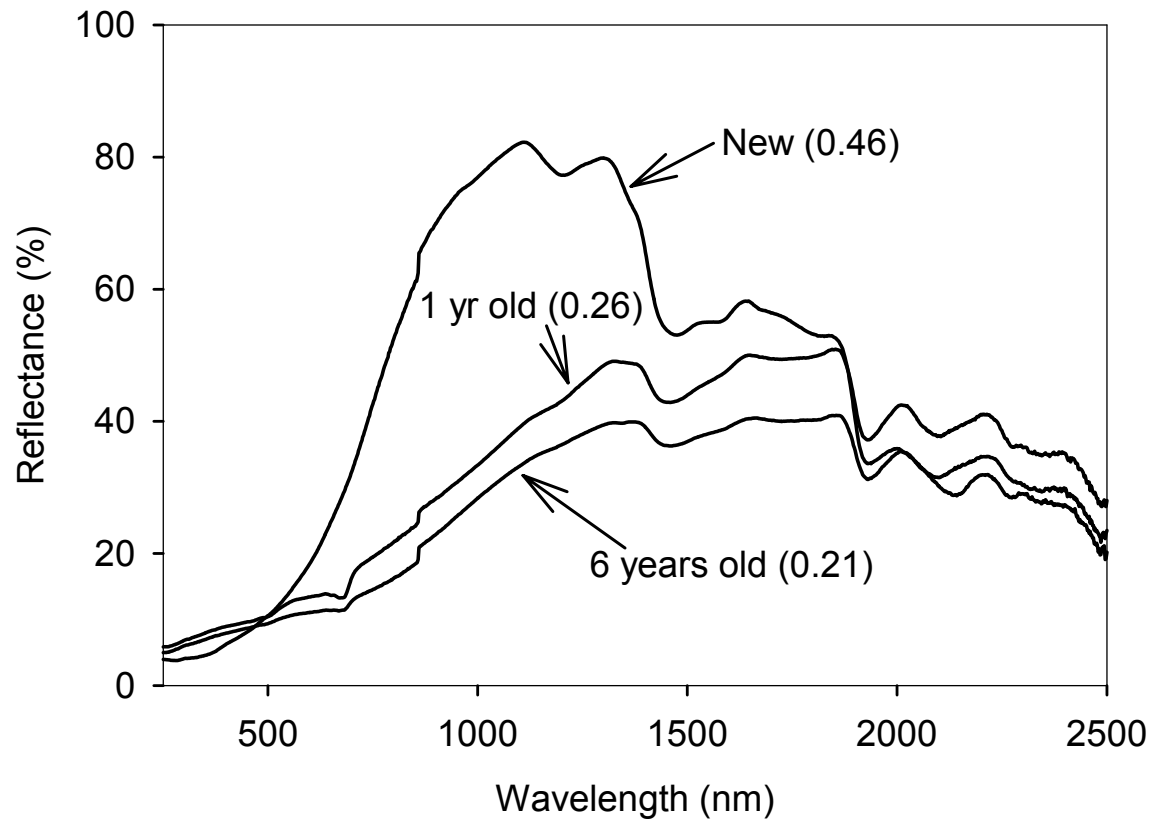


Figure 20. Spectral reflectance of western red cedar roofing shingles. The solar reflectance is 0.46 when new, and declines to 0.21 after 6 years exposure.

Task 2.7: Technology transfer and market plan

The objective of this task was to make cool-colored roofing materials a market reality within three to five years. LBNL, ORNL, color pigment manufacturers and granule manufacturers worked and supported the roofing manufacturers to penetrate the roofing market with new more reflective cool-pigmented colored roofing materials. The project team worked with roofing component manufacturers and color pigment manufacturers to introduce prototype cool-colored asphalt shingles, clay and concrete tiles, metal roofing, and wood shake roof products.

Task 2.7.1: Technology Transfer

The objective of this task was to support the roofing industry by promoting and accelerating the market penetration of cool color pigmented roof products. Both laboratories in conjunction with their respective industry partners presented research results at appropriate trade shows, and published their results in each industry's appropriate trade magazine. The following is a list of articles presented in various trade magazines, conferences, and journal (A copy of each publication can be found in Attachment 11).

Task 2.7.2: Market Plan

The objective of this subtask was to develop and initiate actions to facilitate the market adoption of cool-pigmented reflective roofing products.

The California Energy Commission (CEC) through this project has dramatically advanced the technology of non-white "Cool Roofs" that exploit complex inorganic paint pigments to boost the solar reflectance of clay and concrete tile, painted metal, and asphalt shingle roofing. The project has successfully developed several non-white cool-colored roof products for sloped roofs over the past three years and has shown positive energy savings in residential field tests demonstrating pairs of homes roofed in concrete tile, painted metal and asphalt shingles with and without cool pigmented materials. Without further efforts, the accomplishments achieved by the CEC in its "Cool Roofs" Public Interest Energy Research (PIER) project will creep into the marketplace over the next several decades, slowly bringing the significant energy, cost, smog and carbon savings that the technology promises.

Near the end of the CEC project, the project's 16 industrial partners discussed their needs to further develop and successfully market their residential cool roofing products. Their recommendations and requests are summarized in Table 6.

The opportunity exists to rapidly accelerate the uptake of cool roofing materials. First and foremost, residential cool roofs need to be credited and recommended in the state's Title 24 standards that primarily determine what products are used in the construction of new houses and major remodels. Second, more cool materials for all residential (and commercial) sloped roofing systems must be available and appropriately labeled. Third, the application of appropriate labels on roofing products must become universal. Fourth, architects, designers, builders, roofing material distributors and retailers, and consumers need to learn of the availability and benefits of using cool roofing materials. Fourth, California utilities and the state government can further influence the selection of cool roofs through innovative incentive and rebate programs to accelerate their market penetration. Finally, market penetration can also be accelerated by enhancing the credibility of retailer and utility marketing claims through large-scale demonstrations of cool roofs to consumers, developer, designers, and roofing contractors.

In collaboration with the roofing industry partners, we prepared a market plan for industry/national labs collaborative efforts to help the CEC in deploying cool-colored roofing. The plan focuses on six parallel initiatives: 1) regulate; 2) increase product selection; 3) label; 4) educate; 5) provide incentives; and 6) demonstrate performance. This market plan is enclosed in Attachment 12.

Assistance requested in marketing cool roofs	Industry partner requesting assistance
Continuing education for design build firms, architects, utility consumers, construction professionals and homeowners integrated into seminars offered by the CABEC.	Steelscape, BASF, Custom-Bilt, Shepherd
Software to estimate the cooling energy savings and peak demand reduction achieved by installing cool roofs on specific buildings	Steelscape, BASF, Custom-Bilt, Ferro, Elk, ARC
Monitoring solar reflectance and color change of the materials installed at the California weathering sites	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Elk, ARC
Monitoring solar reflectance, color change, and thermal performance of materials at ORNL test facilities and the Sacramento test homes	Steelscape, BASF, Custom-Bilt, ISP, Elk, Ferro, ARC
Expanding the cool coating database	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Shepherd, 3M
Large-scale demonstration of cool roofs	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Elk, ARC
Predictive software for design of cool coatings	Steelscape, BASF, Custom-Bilt, ISP, Ferro, 3M
Research to increase reflectivity and reduce costs	ISP, Ferro, Elk, 3M, Shepherd, ARC
Tools to accurately measure solar reflectance	ISP, Elk, 3M, ARC
Calculations of weathering benefits of cool roofing	ISP
Identification of new materials and techniques	ISP, Ferro, 3M
Determination of the relationship between granule and ultimate shingle reflectances	3M
Acceleration of cool roof rating criteria by CRRC and Energy Star	3M

Table 6. Industry needs to successfully market their cool roof product

Task 2.7.3: Title 24 Code Revisions

The objective of this task was to prepare a preliminary document of energy and peak demand savings for installing cool roofs in various California climates. This data can be further developed to prepare a proposal for updating the Title 24 to include cool colored roofing materials.

To estimate the energy-savings of cool-colored roofing materials, we calculated the annual cooling energy use of a prototypical house for most cooling dominant cities around the world. We used a simplified model that correlates the cool energy savings to annual cooling degree days (base 18°C) (CDD18). The model is developed by regression of simulated cooling energy use against CDD18. We performed parametric analysis and simulated the cooling- and heating-energy use of a prototypical house with varying level of roof insulation (R-0, R-1, R-3, R-5, R-7, R-11, R-19, R-30, R-38, and R-49) and roof reflectance (0.05, 0.1, 0.2, 0.4, 0.6, and 0.8) in more than 250 climate regions, using the DOE-2 building energy use simulation program. For each prototypical analysis, the parametric analysis led to 15,000 DOE-2 simulations. Then the resulting cooling- and heating-energy use was correlated to CDD18.

The prototypical house used in this paper is assumed to have roofing insulation of 1.9 m²K/W (R-11 insulation). The coefficient of performance (COP) of the prototype house air conditioner is assumed to be 2.3. The estimates of savings are for an increase in roof solar reflectance from a typical dark roof of 0.1 to a cool-colored roof of 0.4. These calculations present the variation in energy savings in different climates around the world. The typical building may not necessarily be representative of the stock of house in all countries. Here, we only report of cooling energy savings; potential wintertime heating energy penalties are not accounted for in these results, although a lessened penalty occurs for sub-tile vented products. Table 7 and Table 8 show potential cooling energy savings in kWh per year for a house with 100m² of roof area for stock of pre-1980 and post-1980 houses, respectively. The savings can be linearly adjusted for houses with larger or smaller roof areas. For most California climates, the application of cool colored roof yields net savings in the range of 100-400 kWh per 100 m² per year. The savings are obviously smaller for buildings with higher roof insulation. For houses that are not air conditioned, cool-colored roofing materials offer comfort, typically at very reasonable costs.

Attachment 13 contains the technical document discussing the potential energy savings in a greater detail.

Roof Insulation Climate Zone	R-5		R-7		R-11		R-19		R-30	
	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)
CTZ1	110	-11	90	-9	67	-7	47	-5	35	-5
CTZ2	172	-9	149	-7	120	-6	93	-4	76	-3
CTZ3	117	-8	97	-6	73	-5	52	-4	39	-3
CTZ4	155	-7	133	-6	106	-5	80	-3	65	-3
CTZ5	116	-8	96	-6	73	-5	51	-3	39	-3
CTZ6	160	-5	137	-4	110	-3	84	-2	68	-2
CTZ7	181	-5	157	-4	127	-3	99	-2	82	-1
CTZ8	214	-5	188	-4	156	-3	124	-2	104	-1
CTZ9	244	-5	215	-4	180	-3	146	-2	124	-1
CTZ10	286	-6	255	-5	216	-3	177	-2	152	-2
CTZ11	292	-8	260	-7	221	-5	182	-4	156	-3
CTZ12	223	-8	196	-7	162	-5	130	-4	110	-3
CTZ13	372	-7	336	-6	289	-4	241	-3	209	-2
CTZ14	350	-9	315	-7	270	-6	225	-4	195	-3
CTZ15	646	-4	593	-3	521	-2	445	-1	393	-1
CTZ16	148	-14	126	-12	99	-10	75	-8	60	-6

Table 7. Estimates of annual cooling electricity savings (kWh) and heating energy penalties (therms) from installation of cool-colored roofs on pre-1980 single-family detached homes with gas furnace heating systems. All savings and penalties are per 100 m² of roof area. Solar reflectance change is 0.2 (for fiber glass asphalt shingles: change of the roof reflectance from 0.1 to 0.3; for clay and concrete tiles: change of the roof reflectance from 0.2 to 0.4). The savings and penalties can be linearly adjusted for other values of changes in solar reflectance.

Roof Insulation Climate Zone	R-11		R-19		R-30		R-38		R-49	
	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)
CTZ1	43	-4	29	-3	21	-2	18	-2	15	-2
CTZ2	73	-3	54	-2	42	-2	38	-2	34	-1
CTZ3	46	-3	32	-2	23	-1	20	-1	17	-1
CTZ4	65	-3	47	-2	36	-1	33	-1	29	-1
CTZ5	46	-3	32	-2	23	-1	20	-1	17	-1
CTZ6	67	-2	49	-1	38	-1	34	-1	30	0
CTZ7	77	-2	58	-1	45	-1	41	0	37	0
CTZ8	93	-2	71	-1	57	-1	51	-1	47	0
CTZ9	107	-2	83	-1	67	-1	61	0	55	0
CTZ10	127	-2	100	-1	81	-1	74	-1	68	-1
CTZ11	130	-3	102	-2	83	-1	76	-1	70	-1
CTZ12	97	-3	74	-2	59	-1	54	-1	49	-1
CTZ13	168	-2	134	-2	111	-1	102	-1	94	-1
CTZ14	158	-3	125	-2	103	-2	95	-1	87	-1
CTZ15	300	-1	244	-1	206	0	190	0	176	0
CTZ16	61	-6	44	-4	34	-3	30	-3	27	-3

Table 8. Estimates of annual cooling electricity savings (kWh) and heating energy penalties (therms) from installation of cool-colored roofs on 1980⁺ single-family detached homes with gas furnace heating systems. All savings and penalties are per 100 m² of roof area. Solar reflectance change is 0.2 (for fiber glass asphalt shingles: change of the roof reflectance from 0.1 to 0.3; for clay and concrete tiles: change of the roof reflectance from 0.2 to 0.4). The savings and penalties can be linearly adjusted for other values of changes in solar reflectance.

Conclusions and Recommendations

Raising roof reflectivity from an existing 10-20% to about 60% can reduce cooling-energy use in buildings in excess of 20%. Cool roofs also result in a lower ambient temperature that further decreases the need for air conditioning and retards smog formation. In 2002, suitable cool *white* materials were available for most roof products, with the notable exception of asphalt shingles; cooler *colored* materials are needed for all types of roofing. To help to fill this gap, the California Energy Commission (Energy Commission) engaged Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL) to work on a three-year project with the roofing industry to develop and produce reflective, colored roofing products. The intended outcome of this project was to make cool-colored roofing materials a market reality within three to five years. For residential shingles, we have developed prototype colored-shingles with solar reflectances of up to 35%. One manufacturer currently markets colored shingles with the ENERGY STAR qualifying solar reflectance of 0.25. Colored metal and clay tile roofing materials with solar reflectances of 0.30 to 0.60 are currently available in the California market.

LBNL and ORNL performed research & development in conjunction with pigment manufacturers, and worked with roofing materials manufacturers to reduce the sunlit temperatures of nonwhite asphalt shingles, clay tiles, concrete tiles, metal products, and wood shakes. A significant portion of the effort was devoted to identification and characterization of pigments to include and exclude in cool coating systems, and to the development of engineering methods for effective and economic incorporation of cool pigments in roofing materials. The project also measured and documented the laboratory and in-situ performances of roofing products. We also established and monitored four pairs of demonstration homes to measure and showcase the energy-saving benefits of cool roofs. The following activities were carried out.

In collaboration with the Energy Commission, we convened a Project Advisory Committee (PAC), composed of 15 to 20 diverse professionals, to provide strategic guidance to the project.

In order to determine how to optimize the solar reflectance of a pigmented coating matching a particular color, and how the performance of cool-colored roofing products compares to that of a standard material, we (1) measured and characterized the optical properties of many standard and innovative pigmentation materials; (2) developed a computer model to maximize the solar reflectance of roofing materials for a choice of visible colors; and (3) created a database of characteristics of cool pigments.

In order to help manufacturers design innovative methods to produce cool-colored roofing materials, we (1) compiled information on roofing materials manufacturing methods; (2) worked with roofing manufacturers to design innovative production methods for cool-colored materials; and (3) tested the performance of materials in weather-testing facilities.

One of the project objectives was to demonstrate, measure and document the building energy savings, improved durability and sustainability attained by use of cool-colored roof materials to key stakeholders (consumers, roofing manufacturers, roofing contractors, and retail home improvement centers). In order to do this, we (1) monitored buildings at California demonstration sites to measure and document the energy savings of cool-colored roof materials; (2) conducted materials testing at weathering farms in California; (3) conducted thermal testing

at the ORNL Steep-slope Assembly Testing Facility; and (4) performed a detailed study to investigate the effect of solar reflectance on product useful life.

We developed partnerships with various members of the roofing industry. We worked through the trade associations to communicate and advertise to their membership new cool color roof technology and products. This collaboration induced the manufacturers to develop a market plan for California and to provide technical input and support for this activity. Through the industry partners, many California housing developers and contractors have been convinced to install the new cool-colored roofing products.

Re-roofing houses with cool products when roofs are due for replacement and specifying cool roofs in new construction are economically sensible ways to significantly increase energy efficiency. The price premium of cool roofs compared to conventional ones is small, and is paid back in air conditioning savings within a few years. When a sufficiently large number of home and commercial building owners adopt cool roofs regionally, urban air temperatures decrease, slowing the rate of smog formation. This improves public health, and helps cities meet federally mandated clean air requirements. Finally, cool roofs reduce peak electrical demand on hot summer afternoons, reducing strain on the electrical grid and helping to avoid blackouts and brownouts.

If applied to cars, cool color technology could improve fuel economy by allowing manufacturers to downsize air conditioning units. These savings could help further reduce greenhouse gas emissions and increase U.S. energy security by reducing reliance on imported petroleum. For all of these reasons Cool Colors, on roofs and in other applications, have a tremendous potential to contribute to the solution of major global problems within a short time, at a reasonable cost.

Recommendations

The California Energy Commission (CEC) has dramatically advanced the technology of non-white “Cool Roofs” that exploit complex inorganic paint pigments to boost the solar reflectance of clay and concrete tile, painted metal, and asphalt shingle roofing. The project has successfully developed several non-white cool-colored roof products for sloped roofs over the past three and a half years and has shown positive energy savings in residential field tests demonstrating pairs of homes roofed in concrete tile, painted metal and asphalt shingles with and without cool pigmented materials. Without further efforts, the accomplishments achieved by the CEC in its “Cool Roofs” Public Interest Energy Research (PIER) project will creep into the marketplace over the next several decades, slowly bringing the significant energy, cost, smog and carbon savings that the technology promises.

Near the end of the CEC project, the project's 16 industrial partners discussed their needs to further develop and successfully market their residential cool roofing products. Their recommendations and requests are summarized in Table 6.

The opportunity exists to rapidly accelerate the uptake of cool roofing materials. First and foremost, residential cool roofs need to be credited and recommended in the state's Title 24 standards that primarily determine what products are used in the construction of new houses and major remodels. Second, more cool materials for all residential (and commercial) sloped roofing systems must be available and appropriately labeled. Third, the cool roofing pigment database should be maintained and expanded with new materials in order to assist the industry to develop new and advanced materials at competitive prices. Fourth, the aging and weathering of cool

roofing materials and their effects on the useful life of roofs need to be further studied. Fifth, the application of appropriate labels on roofing products must become universal. Sixth, architects, designers, builders, roofing material distributors and retailers, and consumers need to learn of the availability and benefits of using cool roofing materials. Seventh, California utilities and the state government can further influence the selection of cool roofs through innovative incentive and rebate programs to accelerate their market penetration. Eighth, for utilities to develop incentive programs and for manufacturers to coordinate their materials development with their marketing efforts, they need to have an industry-consensus calculator to accurately estimate energy and peak demand of cool colored roofs. The calculator should account for both the cooling energy savings and potential heating energy penalties of cool roofs. Finally, market penetration can be accelerated by enhancing the credibility of retailer and utility marketing claims through large-scale demonstrations of cool roofs to consumers, developer, designers, and roofing contractors.

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Attachment 1: Task 2.4.1 reports.
Attachment 2: Task 2.4.2 reports.
Attachment 3: Task 2.4.3 reports.
Attachment 4: Task 2.5.1 reports.
Attachment 5: Task 2.5.2 reports.
Attachment 6: Task 2.5.3 reports.
Attachment 7: Task 2.6.1 reports.
Attachment 8: Task 2.6.2 reports.
Attachment 9: Task 2.6.3 reports.
Attachment 10: Task 2.6.4 reports.
Attachment 11: Task 2.7.1 reports.
Attachment 12: Task 2.7.2 reports.
Attachment 13: Task 2.7.3 reports.